Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at http://about.jstor.org/participate-jstor/individuals/early-journal-content.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

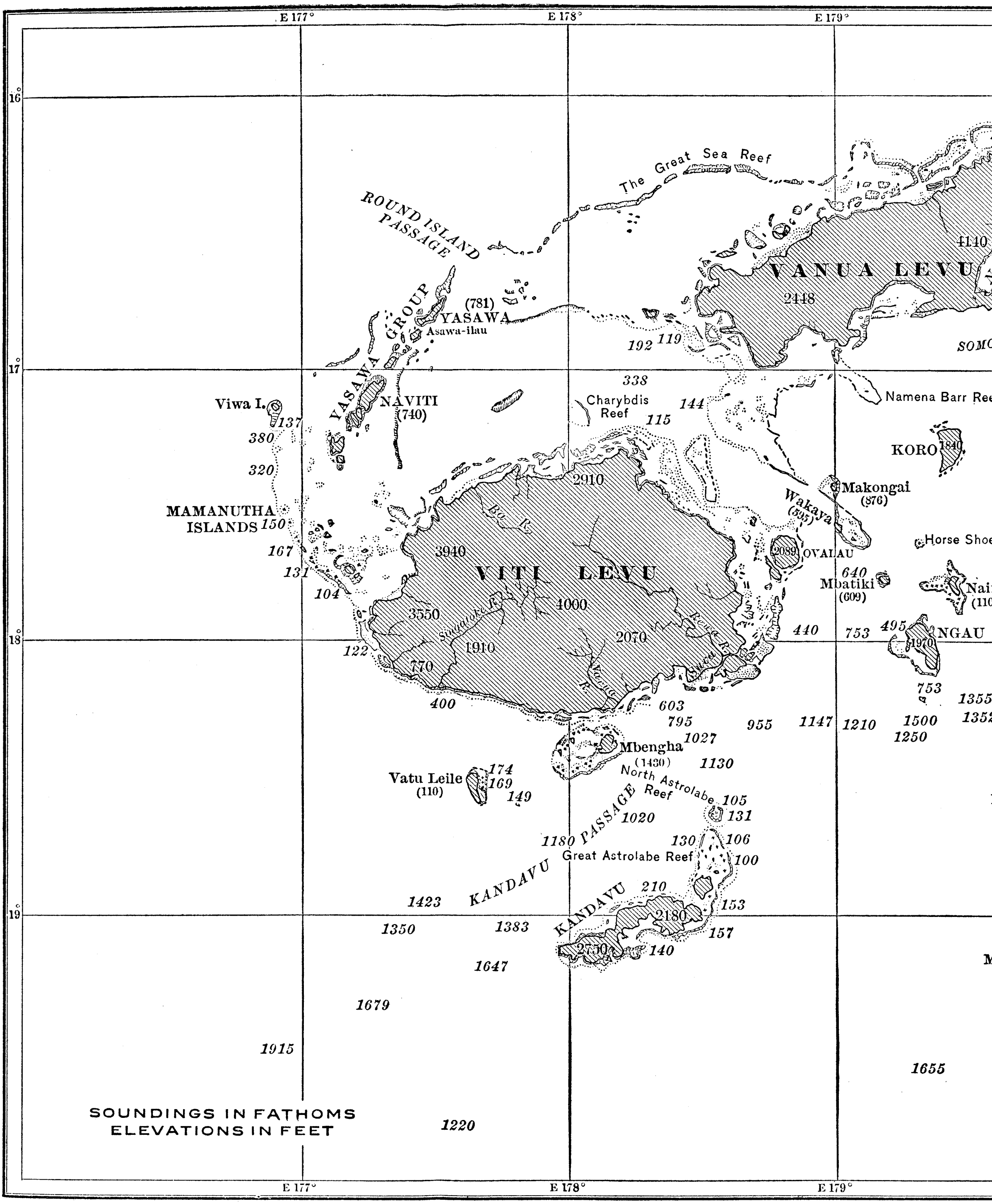
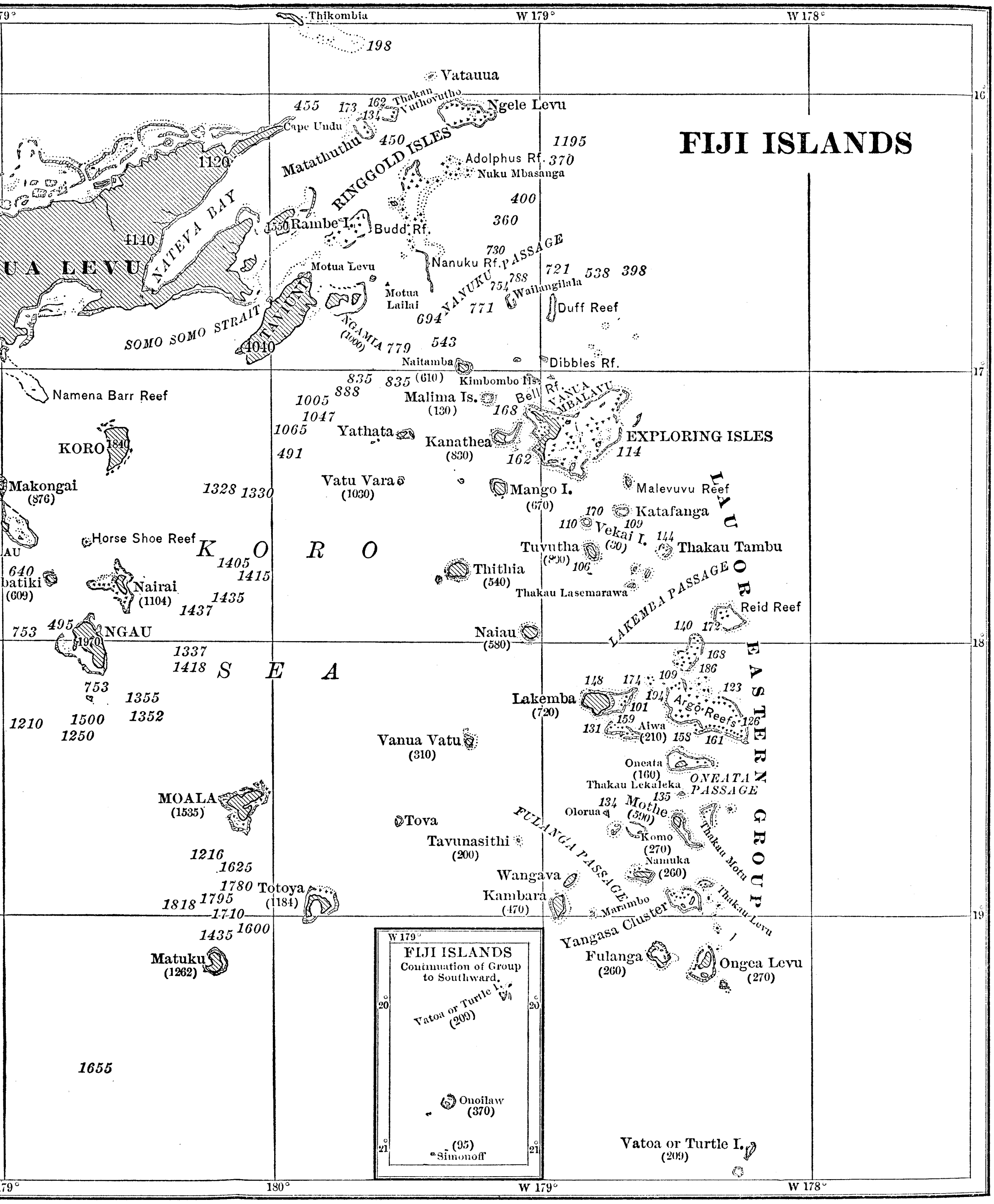


Chart of the Fiji Isl

Map copied from A. Agassiz, Fiji Islands and Coral Reefs, Bull. Mus. Comp. Zoöl., Harvard College, Vol. 33,



t of the Fiji Islands

l College, Vol. 33, (1899), Plate 2. Scale, 1: 2,200,000, which was reduced from Admiralty Chart No. 2691.

GEOLOGICAL OBSERVATIONS IN FIJI.

By Wilbur G. Foye.

PART I.—GEOLOGICAL HISTORY OF FIJI.

TABLE OF CONTENTS.

Page.
Introduction 5
Itinerary 6
Previous Work 8
Abstract 9
Geological History of Viti Levu 10
  Physiography 10
  Western Viti Levu 11
    Singatoka District 11
    Yasawa Group 17
    Outline of the Geological History of Western Viti Levu . . 19
  Eastern Viti Levu 20
  Comparison of Results with Those of Previous Workers 25
Geological History of Vanua Levu 26
  Introduction 26
  Physiography 26
  Lambasa District 27
  Northern Coast of Vanua Levu, East of Lambasa 30
  Mbutha Bay District 31
  Southern Coast of Vanua Levu 33
Taviuni 37
Comparison of the History of Vanua Levu with that of Viti Levu . . 41
Geological History of the Smaller Islands, Especially of the Lau Group 43
    Introduction 43
  Group I — Islands Composed of Limestones and Volcanic Rocks 44
    Exploring Group 44
      Vanua Mbalavu 46
      Avea 49
      Yanu Yanu 50
      Malatta 50
      Susui 51
      Thikombia-i-lau 52
    General Remarks on the Exploring Group 54
    Tuvuthá 56
    Lakemba 58
    Ono-i-lau 61
    Kambara 65
  Group II — Islands Composed Wholly of Limestone 69
    Introduction 69
    Wangava 69
    Ongea 71
    Vatoa 72

PAGE.
Fulanga 74
Vekai 76
Group III — Volcanic Islands 76
Introduction 76
Munia 77
Kanathea 79
Mbengha 80
Kandavu 81
General Review of the Geological History of Fiji 84
List of Fossils 85
Bearing of the Results of the Expedition on the Coral Reef Problem 88
Summary of Theoretical Results 94
Bibliography (See end of Part II) 143

ILLUSTRATIONS.

Frontispiece. Chart of the Fiji Islands 2
Figure 1. Cross-section of Falls Contact, near Wai Mbasanga, Viti Levu 12
Figure 2. Mouth of the Singatoka River as seen from the Northeast . 14
Figure 3. Geological Sketch Map of Southwestern Viti Levu . . . 15
Figure 4. Structural Dips in Southwestern Viti Levu 16
Figure 5. Cross-section of the Northern End of Nathula, Yasawa Group 17
Figure 6. Yasawa-i-lau as seen from the Southwest 18
Figure 7. Fault at Southern End of Yasawa-i-lau 18
Figure 8. View of the Southern Coast of Viti Levu, near Tangani . 21
Figure 9. Sketch Map of the Navua Delta-plain 22
Figure 10. Sketch Map of the Lambasa Delta-plain 27
Figure 11. View of the Lambasa Delta-plain 27
Figure 12. Cross-section of an Elevated Coral-reef near Lambasa, Vanua Levu 28
Figure 13. Embayments about Mbutha Bay, Vanua Levu 32
Figure 14. Sketch Map and Cross-section of an Elevated Coral-reef near Vunilangi, Vanua Levu 34
Figure 15. Ndela-ni-koro, near Nandi, Vanua Levu 35
Figure 16. View of an Elevated Coral-reef near Nandi, Vanua Levu . 36
Figure 17. Columnar Section of an Elevated Coral-reef near Nandi, Vanua Levu 36
Figure 18. Sketch Map of Taviuni 38
Figure 19. View of Ngamia and Northwestern Taviuni from Nangasau 40
Figure 20. Geological Sketch Map of Vanua Mbalavu, Exploring Group 45
Figure 21. Sketch Map of Avea, Exploring Group 49
Figure 22. Sketch Map of Malatta and Susui, Exploring Group . . 51
Figure 23. Profiles of Four Limestone Islands of the Lau Group . . 52
Figure 24. Sketch Map of Thikombia-i-lau, Exploring Group . . . 53
Figure 25. Sketch Map and Profile of Tuvuthá 57
Figure 26. Sketch Map of Lakemba 58
Figure 27. Sketch of Spur-hills, Northern Lakemba 59
Figure 28. Sketch Map of Ono-i-lau 61

		Page.
Figure 29.	Profiles of Ndoi, Ono-i-lau	62
Figure 30.	View of Ndui from Ono Levu	63
Figure 31.	Sketch Map of the Islands of Kambara, Wangava and Marambo	66
Figure 32.	Sketch Map and Profile of Ndelai Yaloi, Kambara	67
Figure 33.	Profile of Wangava as seen from Kambara	70
Figure 34.	Sketch Map and Profile of Ongea	71
Figure 35.	East-West and North-South Profiles of Vatoa	72
Figure 36.	Typical Cross-section of a Barrier Reef	73
Figure 37.	Sketch Map of Fulanga	74
Figure 38.	Hachure Map and Profile of Munia, Exploring Group	78
Figure 39.	View of Mbengha as seen from the Northeast	80
Figure 40.	Cross-section of Elevated Limestones near the Village of Kandavu, Kandavu	83

INTRODUCTION.

The difficulty of finding conclusive evidence concerning the nature of the foundations on which coral reefs stand has led to prolonged discussion of the coral reef problem. During this discussion Darwin's theory of the origin of atolls has been the storm center.

The earlier investigators studied the reefs with little reference to the adjacent lands. Among them, Dana (1853, p. 118) alone saw that the reef and the land form back of the reef were intimately connected; that the history of one was written, in part, in the outline of the other. In the last few years, W. M. Davis has emphasized the importance of embayed shorelines behind barrier reefs. The abundance of these features, which Darwin neglected in the announcement of his theory, and the numerous cases of coralliferous limestone resting unconformably on eroded rocks, has led Davis to believe that Darwin's theory is correct.

A luxuriant tropical vegetation has rendered it often difficult to determine the structure of the upraised coral limestones and the nature of their contact with the underlying rocks. It is evident that such data are very important to the coral reef problem. For example, the structure of a reef which develops on an outward-growing platform of its own débris during a stillstand of the ocean level, as postulated by Sir John Murray (1880, p. 517), will not be the same as that of a reef formed on a subsiding volcanic mass, according to Darwin's theory.

With the hope that the study of the structure of the central islands, surrounded by coral reefs, might throw new light on the problem, the writer journeyed to Fiji in June, 1915. This subject as well as other geological problems presenting themselves during the progress of the investigation are discussed in the following pages.

The writer is deeply indebted to the Committee on Sheldon Traveling Fellowships of Harvard University for a generous grant of funds which made the exploration possible. He also wishes to thank the Division of Geology of the University for many kindnesses, especially for a grant from the Shaler Memorial Fund with which to complete the preparation of this report. Nor can he fail to express his sincere gratitude to many friends in Fiji who kindly welcomed a stranger and gave of their time and substance for his aid.

ITINERARY.

After a brief visit to the modern volcanoes of the Hawaiian Islands the writer went immediately to Suva, the capital of Fiji, situated on a beautiful bay at the southeastern side of Viti Levu.

During the latter part of July a brief excursion was made with Mr. Stewart, Assistant Secretary for Native Affairs, to the volcanic island of Mbengha, a few miles southwest of Suva. The beginning of August found the writer en route for the Lau or Eastern group, aboard the inter-island steamer, "Amra." A stop of half a day was made at Levuka, the old capital of Fiji, situated on the volcanic island of Ovalau, near the eastern coast of Viti Levu. Stops of a few hours were also made at Thithia and Mango, but little geological work could there be accomplished.

At Loma Loma, a village on the southeastern side of Vanua Mbalavu, one of the Exploring Group, the writer was cordially received by Dr. St. Johnston, the Government District Commissioner for the Lau Group, and, thanks to letters given by the Honorable Mr. Allardyce, Commissioner of Native Affairs, and the Honorable Mr. Hutson, Colonial Secretary, an extended exploration of this group was made possible. The month of August was largely occupied by a tour of the various islands of the Exploring Group — Vanua Mbalavu, Malatta, Susui, Munia, Thikombia-i-lau, and Avea. An adjacent island to the west, Kanathea, was also visited.

September, October, and part of November were spent in travelling by cutter among the smaller islands south of the Exploring Group.

The Vekai Reef was first visited; then Tuvuthá, Lakemba, Fulanga, Ongea, Vatoa, and Ono-i-lau, the southernmost island of the group. Returning northward, Kambara and Wangava were visited en route for Lakemba. In most cases no more than a day's sojourn at each island was possible, but, owing to the difficulty of obtaining transportation by cutter, a week or more was spent at Ono and two weeks at Lakemba.

From Lakemba, Loma Loma was reached again, and thence by the steamship "Amra," the voyage was made to Taviuni, a large island east of Vanua Levu. The Government physician at Taviuni, Dr. Trotter, gave valuable assistance by furnishing transportation facilities about the island. Leaving Taviuni by cutter the writer saw in the distance Goat Island, lying just off the west coast of Taviuni, and Kioa, an island east of Vanua Levu. Several points on Mbutha Bay, at the extreme eastern side of Vanua Levu, were then visited and a journey made across the Waikava peninsula, forming the extreme southeastern point of the island. This journey allowed 20 to 30 miles of the southeastern coast of the island to be explored; but the isthmus south of Natewa Bay, the long inlet on the eastern side of the island, was not visited. From Mbutha Bay via the island of Rambi the route led to Lambasa, a town on the northern coast of Vanua Levu. At the latter place, the railroad and other facilities, owned by the Colonial Sugar Refining Company, were kindly put at the disposal of the writer and 30 miles of the coast east of Lambasa were traversed, largely by railroad but partly on foot. A walk across the central ridge of the island enabled the writer to see Savu Savu Bay on the southern coast and obtain a clear idea of the geology of the central portion of this island.

On returning to Lambasa, passage was taken in the "Amra" for Suva. The boat touched at Lauthala (a small island east of Taviuni), at Taviuni, and at Levuka. The short voyage from Suva to Navua, a town lying west of Suva, was made by a small launch, running entirely within the barrier reef. After a week's stay at this town, the journey back to Suva was made by launch. From Suva the Government's steamship, the "Ranandi", enabled the writer to reach Lautoka on the extreme western side of the island of Viti Levu.

After a day at Lautoka, Mba, a town some 30 miles north of Lautoka, was reached by railway.

From Mba, the voyage to the Yasawa Group lying northwest of Viti Levu was made by cutter. During a week's stay in this group, the islands of Nathula, Naviti, and Yasawa-i-lau as well as several small islets, were visited.

Returning to Mba, the entire western side of Viti Levu was traversed by railroad, while the southwestern coast was traversed on foot. A journey of 45 miles inland along the course of the Singatoka River, a river which flows across west central Viti Levu and drains more than a third of the island, led the writer to the plutonic rocks forming a conspicuous part of its central portion. Much of the success of this trip was due to the assistance of the District Commissioner of the Singatoka district, Mr. James Stewart.

From the Singatoka district, Suva and then Kandavu were reached by cutter. Owing to the kindness of Mr. Alcock, the District Commissioner of Kandavu, an extended tour was made possible along the eastern coast of the island, north of Vunisea. Several of the smaller islands, within the Kandavu Reef and north of the main island, were also visited. Among these were Ono and Ndravuni. The small island of Solo, within its own reef, lying north of the Kandavu reef, was the goal of one voyage, whence Vunisea was reached, travelling along the western side of Kandavu.

The writer then returned to Suva, in the middle of February, 1916, and, after a few traverses up the rivers about Suva Bay, sailed for the United States.

PREVIOUS WORK.

Many of the students of the coral reef problem have visited Fiji. Darwin sailed through the group while on his voyage in the "Beagle" but did not land. Dana spent three months among the islands and his results are published as a volume of the report of the United States Exploring Expedition under Commodore Charles Wilkes (1844, pp. 337–352). Professor Dana (1853, p. 135) concluded that while an uplift of 5 to 6 feet characterized the western portion of the group, subsidence had taken place to the east.

About the year 1896, J. Stanley Gardiner (1898, pp. 495–496) of Cambridge University, England, visited a large number of the islands. He concluded that his observations afforded, "strong reasons against Darwin's and Dana's theories of the structure and formation of coral reefs in general and those of Fiji in particular." From a study of the island of Fulanga, one of the eastern group, he was led to believe with Murray that lagoons may be formed "by the wearing and dissolving action of sea water."

In 1897–98, Alexander Agassiz (1899, p. 43) visited the islands in the steam yacht, "Yaralla." He saw evidence of uplift, rather than subsidence, on every side, and was led to abandon Darwin's theory as untenable. He concluded that the coral reefs developed on platforms eroded on uplifted limestone by the action of the sea.

E. C. Andrews (1900) examined the limestones in the field. The island of Mango, one of the Lau group, was studied specially and it was concluded that the volcanic rocks of the island were erupted later than the upraised limestones. The limestones of Vanua Mbalavu were described under two classes: as compact, bedded limestones, and as limestones of reef-rubble origin.

In 1903, W. G. Woolnough (1903, p. 457 and 1907, pp. 431 to 473) made a rapid trip across Viti Levu and was the first to describe granites from specimens collected "in situ."

During the years 1896 to 1899, Guppy (1903) made a very detailed study of the island of Vanua Levu. His chief conclusion was that "Vanua Levu is a composite island built up during a long period of emergence, that began probably in the later Tertiary period, by the union of a number of large and small islands of volcanic formation representing the products of submarine eruptions."

More recently (1914–15), Davis (1915, p. 251) visited the group and described the island of Vanua Mbalavu as an ideal example of a barrier reef formed, according to Darwin's theory, during the subsidence of a central, eroded, volcanic mass.

ABSTRACT.

1. The larger islands of Viti Levu and Vanua Levu have central cores of deeply eroded plutonic rocks and are thought to be remnants of an older continental mass.

2. There have been four periods of vulcanism in Fiji. An early period of rhyolitic eruptivity was followed, without a perceptible erosion interval, by a first period of andesitic eruptivity. After erosion and subsidence, a succeeding uplift was accompanied by a second period of andesitic eruptivity. Erosion and renewed subsidence were followed by another period of uplift initiating a series of basaltic eruptions.

3. There are two series of sedimentary rocks in Viti Levu. The folded series of the interior resemble the folded series of the New Hebrides, which Mawson believes to be Miocene. The coastal-plain series have low dips and, by fossil evidence, are apparently post-Tertiary in date.

4. The uplifted, marine, volcanic rocks of Vanua Levu and the elevated limestones of the Lau and Yasawa islands are held to be Pleistocene or Recent and allied in age to the coastal-plain series. All of these rocks were uplifted without folding.

5. The folding of the rocks of the interior of Viti Levu corresponds to the trend lines discerned by Suess elsewhere in Oceania.

6. As far as observed, the elevated limestones of Fiji rest unconformably on eroded volcanic rocks. They were deposited during the subsidence of eroded volcanic islands and are believed to have formed atolls and barrier reefs.

7. An adaptation of Darwin's theory is especially well illustrated in Fiji, since the earth's crust here has been so unstable. Most periods of subsidence have been accompanied by reef formation.

8. There has been a positive shift of sea-level on many of the islands during late geological time. The two main factors which have produced the shift are subsidence and the return of waters to the ocean after the Glacial period. No criteria have been found to evaluate the relative importance of the two factors.

9. The reduction of masses of elevated limestone to sea-level by atmospheric solution and the submergence of the platforms thus formed have produced conditions favorable to the upgrowth of barrier reefs and atolls.

10. Certain reefs near Suva are growing on the delta flat of the Rewa River, as did other, now uplifted, reefs in a previous epoch.

11. The barrier reefs, east of Lakemba and northwest of Viti Levu, are believed to have developed in part as a result of the downward tilting of the earth's crust in recent times.

12. Limestones, buried beneath volcanic rocks, are exposed at the southeastern side of Kandavu. The erosion types in the island indicate an extended history.

GEOLOGICAL HISTORY OF VITI LEVU.

Physiography.

The island of Viti Levu is elliptical in shape. It is 94 miles long from east to west, and 55 miles broad. The southeastern side of the island and a large portion of the eastern side is a low delta flat, overgrown with mangrove bushes. The flat merges into a young, narrow coastal plain which extends from 5 to 10 miles inland where it meets an uplifted mass of marls, a former delta plain now carved into mature hills 70 to 100 feet in height. The older delta plain slopes gradually upward for 5 or 6 miles from its edge, until it rests unconformably against the interior volcanic hills, at heights of 600 or 700 feet.

These volcanic hills form the coast-line for the greater part of the circumference of the island, except near its eastern border. Near the shore the surface is usually maturely eroded, but farther inland various irregular forms, called by the natives spines, thumbs, and twin sisters, give the sky-line a very serrate appearance.

The whole interior is characterized by irregular hills, though quite extensive flats are sometimes found near the rivers. The rocks forming the interior hills are frequently sandstones and marls, in contrast to the volcanic rocks along the coast.

The western and northern shores of the island are very irregular; drowned valleys abound. Many of the valleys are filled with delta deposits, and even small boats find difficulty in entering the river mouths through the tangle of mangroves.

In general the eastern side of the island is well watered; vegetation is abundant. Gorgeous fern forests crown the hilltops, and the higher peaks have giant trees hung with beautiful, trailing mosses.

The western side is usually very dry; trees grow only along the stream beds. An impenetrable growth of reeds covers the hills. The rocks here are deeply lateritized and ravines cut the red and yellow hill slopes.

Western Viti Levu.

Singatoka District.

The Singatoka river has incised a narrow valley in the mature hills of western Viti Levu. Occasional flood-plains border the river, but more often its banks are formed by volcanic hill slopes. In the interior of the island, where loose marls and sandstones abound, flood-plains are much more frequent than nearer the coast where andesitic flows resist erosion.

About 40 miles inland from the southwestern shore of Viti Levu, the Singatoka river and its southern branches cut into a series of plutonic rocks. The central portion of the mass consists of granite and diorite, but near its border there is an ancient, rolling topography carved on gabbroid rocks, which has been flooded by later andesites. Slates and red sandstones were found in the stream beds associated with the diorites and gabbros. One diorite boulder had an inclusion which resembled slate. The actual contact of these rocks was not seen, but, from the inclusion of slate in the diorite, it is inferred that the plutonic rocks intrude the slates and sandstones. The andesites which flooded the gabbro hills were later eroded and depressed beneath the sea. At a water-fall on the northern side of the Singatoka, a coralliferous limestone mingled with pebbles of the andesites lies unconformably on the lava flows. The basal layer is but two or three feet in thickness and grades upward into a sandstone which is overlain conformably by marls and claystones. Occasional beds of brown coal, a few inches in thickness, are interbedded with the marls.

The lava flows represent a thickness of 300 or 400 feet, while the marls and sandstones are 500 or 600 feet in thickness and are overlain conformably by 200 or 300 feet of a massive-bedded limestone. The dips of these rocks are 50° to 85° N., and their general strike somewhat north of east. The limestones are frequently so folded that they are transformed to blue marble. Masses of the limestone form residual, flat tops to many of the interior hills, each covering areas two or three square miles in extent. The sketch shows the rock relations at the contact near the falls. (Figure 1.)

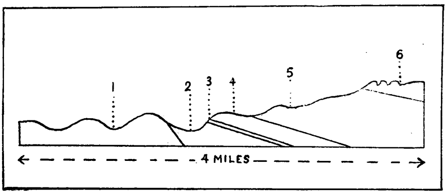


FIGURE 1. Cross-section of Falls Contact, near Wai Mbasanga, Viti Levu. 1 — Gabbro and syenite hills. 2 — Andesitic flows. 3 — Basal conglomerate (2 feet) with coral heads. 4 — Marl. 5 — Claystone and marl with occasional brown coal seams. 6 — Massive limestone.

About 12 miles from the present southwestern coast-line of the island, near the small town of Tumbairata, the rock types just described disappear and volcanic agglomerates and ash-beds replace them. No contacts were seen, but as the dips of the ash beds were low, in contrast with those of the folded sediments, it was inferred that the andesitic agglomerates were more recent than the marls and sandstones of the interior.

Seven miles from the coast, near Narata, a boulder conglomerate, with pebbles and boulders 12 to 14 inches in diameter, was found. The boulders are largely of andesitic material, very rarely of limestone. There is little paste in the conglomerate but occasional layers of gravelly sandstones are interbedded with it. These beds dip 8° to 10° S. While no contacts were seen, it is reasonable to suppose that the conglomerate was eroded from, and overlies, the agglomerate and limestone formations which outcrop on the north. From this point southward, sedimentary rocks occur which have the same general character as those found at Narata, save that the size of the grain becomes smaller and smaller as one approaches the sea. At Yalava, gravel deposits appear; at Tusuirewa, three miles from the mouth of the river, the rocks exposed are marls and sandstones. All these deposits have low dips and form part of an old, uplifted coastal plain.

Near the mouth of the river and for several miles along the coast on either side, there is a series of maturely eroded hills of deeply lateritized andesitic flows and agglomerates. About these andesitic masses, the sandstones and marls of the ancient coastal plain were deposited and later were partially eroded away. At present, coral limestones, which were formed in the quieter waters off the ancient shore-line, cover the hills near the sea; farther inland sandstones and marls occur.

Coral limestones, interbedded with marls and fine conglomerates, are found along the coast for 15 or 16 miles on either side of the mouth of the Singatoka river. The limestones form lenticular beds which often pinch out abruptly. They appear at elevations up to 150 feet and are extensively eroded.

About 12 miles west of the Singatoka, at the little town of Na Sana Sana, a diabasic dike, five feet in width, cuts the limestone. There has been igneous activity, therefore, subsequent to the formation of the narrow coastal plain.

The accompanying sketch (Figure 2) illustrates the topography at the mouth of the Singatoka river. A low point of coralliferous limestone juts out from the eastern bank. The limestones rise 75 feet on the side of an andesitic hill, a quarter of a mile back from the shore, from which the sketch was made. To the west, rolling sand hills, approximately 150 feet in height, extend for two or three miles along the coast. The dunes are travelling westward.

The conditions here are very different from those found at the mouth of the Rewa. The latter river drains a volcanic country, and the lateritized clays are swept down in great abundance. The mouth of the river is a wide mud-flat overgrown with mangrove bushes. The Singatoka, on the other hand, drains a region of granites, diorites, and sediments formed from these rocks. The material, transported by the river, is, therefore, less finely pulverized and is not carried far out to sea. It is also less cohesive above the low-tide mark, dries out quickly, and is blown by the wind into sand hills. Under such conditions corals grow close to the mouth of the Singatoka and, as the sketch shows, the boat passage is very narrow, being kept open only by the scour of the river and tidal currents.

Figures 3 and 4 indicate the areas of marl and coralliferous limestone forming the upraised coastal plain along the southwestern shore of Viti Levu. The belt is never very wide, varying from a half mile to two miles. At the extreme southwestern point of the island, near the small island of Songo, the deposits cease, and it is important to note that here the fringing reef changes to a barrier reef and sweeps out beyond the volcanic islands of the Malolo Group.

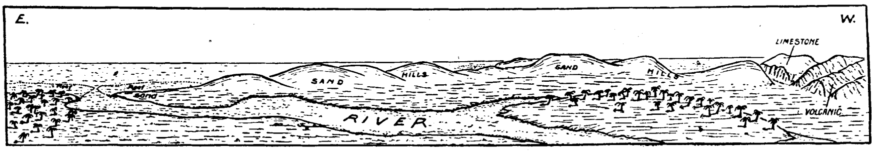


FIGURE 2. Mouth of the Singatoka River as seen from the Northeast.

The depth of water within the Malolo lagoon, back of the reef, gradually increases toward the northwest, from 13 fathoms to 40 and 50 fathoms. The character of the reef correspondingly changes. Near the main island it is quite continuous; farther northwest it becomes more and more patchy and at last disappears entirely.

At first, one might be tempted to correlate the uplift of the coastal sediments east of Songo with the general subsidence to the west, which has embayed the western coast of Viti Levu, thus regarding these movements as part of a single warp affecting the whole island within recent times. Structural evidence from the western coast of Viti Levu and from the Yasawa islands shows that the formation of the lagoon and the barrier reef cannot be ascribed to a single tilting movement toward the west.

It is true that the western coast of the large island is deeply embayed, but there has been uplift along this coast since the embayment. The Nandi River, for example, has a wide, alluvial valley extending for 8 miles inland. Near its mouth, residual hills rise 60 to 75 feet above the general level of the plain. Some of these hills are composed of a red clay, the lateritized product of andesitic rocks. Other hills are made of loose river gravels which unconformably overlie the volcanic rocks and must have been uplifted recently. Again, masses of uplifted coral limestone exist at the northwestern side of the lagoon, among the Yasawa islands. The positions of the masses cannot be accounted for by a single tilting movement.

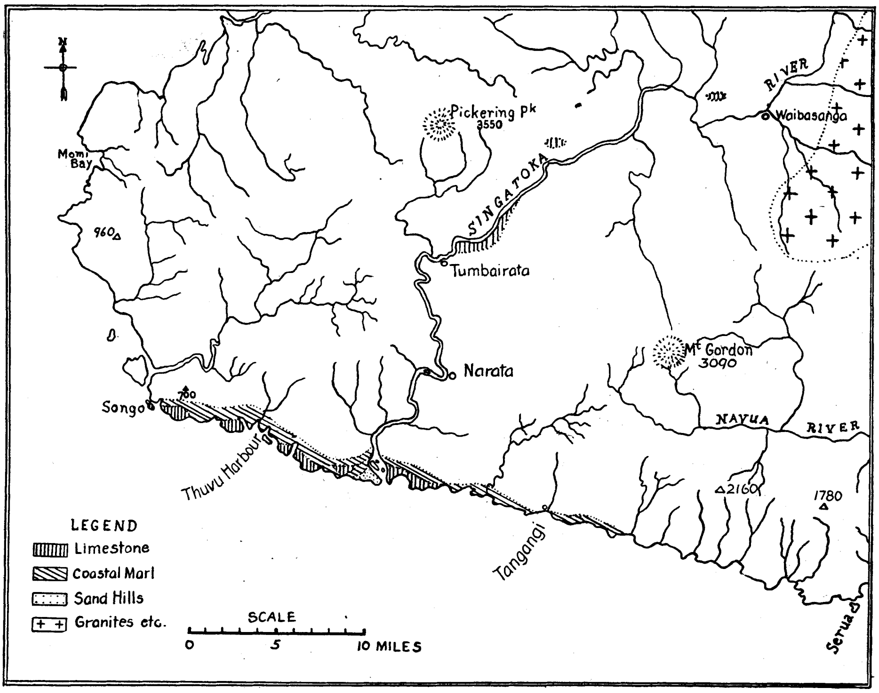


FIGURE 3. Geological Sketch Map of Southwestern Viti Levu.

A study of the recently established shore-line of southwestern Viti Levu and the older, eroded topography of the limestones of the

Yasawa group and eastern Viti Levu, near Suva, has led the writer to postulate the following history for Malolo lagoon and reef.

1. The lagoon was initiated by the extensive submergence of Viti Levu during the period in which the coastal-plain sediments were deposited. The sediments formed a wide submarine flat about the older, folded mass of the island.

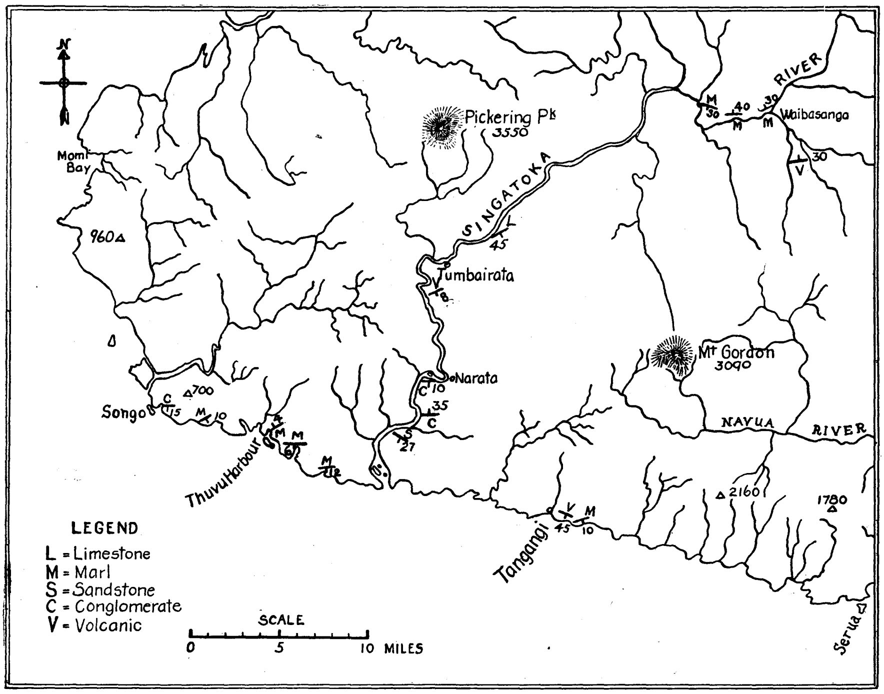


FIGURE 4. Structural Dips in Southwestern Viti Levu.

2. The western portion of the flat was then warped in such a way that the Yasawa limestone was raised above the sea, forming the western side of a trough. The western rivers of Viti Levu, draining into the eastern side of the trough, were drowned by local subsidence and a contemporaneous upwarp caused the emergence of the coastal series at the eastern side of the island, near Suva.

3. A period of erosion followed, after which volcanoes developed

within the Yasawa group burying with their ash the eroded limestones of that area.

4. The volcanic cones were then eroded to sub-maturity and in comparatively recent times have been submerged.

5. The uplift of the Nandi river gravels and of the coastal series near the mouth of the Singatoka river in southwestern Viti Levu occurred during the recent submergence of the Yasawa islands.

There has been, therefore, a slight tilting of the lagoon in recent times towards the northwest, but the lagoon and its bordering reef did not originate with this movement. It is a much older feature.

Yasawa Group.

Lying along the western edge of the lagoon which has just been described is a series of islands the southern members of which are known as the Malolo group, and the northern, as the Yasawa group. Most of these islands are composed of andesitic rocks, sub-maturely eroded. Their coastal outlines offer some of the best examples of embayed topography to be seen in Fiji.

A few of the islands contain elevated limestones, the rocks of special importance in the present investigation. Viwa, the most westerly island of the Fiji Archipelago, is low, flat, and composed of upraised coralliferous limestone with a central hill about 20 feet in height. Lacking means of visiting this island, the writer devoted his time to the two other islands showing coralliferous limestone, namely Nathula and Yasawa-i-lau.

Nathula, one of the northern islands of the Yasawa group, has a rough interior of elevated peaks bounded by sheer cliffs. Its coast-line is very irregular and is fronted by numerous dismembered islets. At its extreme northern end, a small area of sandy limestone was found to contain pelecypod shells and coral, mingled with blown, angular bits of andesitic glass and augite crystals. The area forms a point not over an acre in extent. The limestone has a dip of 25° E. and is much brecciated, owing to the intrusion of a fine grained dike of andesite (Figure 5).

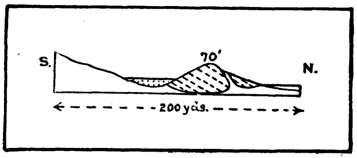


FIGURE 5. Cross-section of the Northern End of Nathula, Yasawa Group.

White—intrusive basalt. Dashed — elevated limestone. Dotted—sandy flats.

A few isolated islets of limestone, on the north, connect this point with the larger island, Yasawa-i-lau, which is entirely composed of limestone. It is about 700 feet high and is honeycombed with a network of caves, many of which extend below sea-level and in which the tide rises and falls. The adjoining sketch of the island was made from the northern side of Nathula (Figure 6).

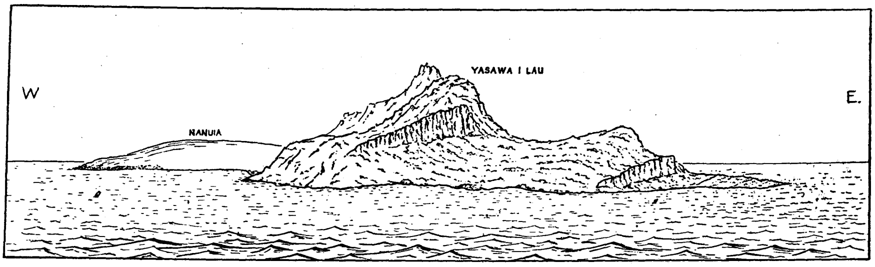


FIGURE 6. Yasawa-i-lau as seen from the Southwest.

The southern end of Yasawa-i-lau is composed of a sandy limestone similar to that composing the northern end of Nathula. Lenses of andesitic waste are interbedded with a glomeratic limestone. These beds are overlain by a more massive, coralliferous limestone, faulted down against them (Figure 7). The nature of the andesitic material interbedded with the limestone leads to the conclusion that volcanic activity was going on at the time the limestone was deposited.

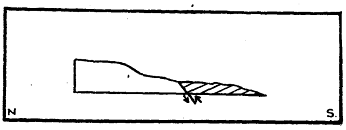


FIGURE 7. Fault at Southern End of Yasawa-i-lau.

Nañuia, a small island just north of Yasawa-i-lau, is connected with the latter by sand-bars which are exposed at low tide. Various under-cut islets of limestone dot the lagoon between the islands and occur also along the south side of Nanuia. Nanuia is a volcanic island made up of interbedded agglomerates and basalt flows. No contact between the limestone and the basalt could be found, though the limestone of the islets was seen within twenty feet of the volcanic rock. However, inasmuch as islands of volcanic ash, deposited under subaerial conditions, are found very close to Yasawa-i-lau with their bedding dipping towards the limestone cliffs, and since the outcrop of limestone at the northern end of Nathula is intruded by an andesitic dike, it was inferred that the volcanic rocks were erupted after the uplift and dissection of the limestone.

It is difficult to correlate the history of the Yasawa group with that of Viti Levu. In discussing the origin of the great barrier reef, it was stated that the lagoon was probably an old feature and had experienced a number of uplifts and depressions. The spine-like mass of limestone in Yasawa-i-lau is but a remnant of a formation once much more extensive. The destruction of so much elevated limestone can only mean that prolonged erosion has affected the area now occupied by the broad lagoon.

There is no reason to suppose that the Yasawa limestones are older than those of the Lau group, which will be described later. The limestones of Lau were elevated during, or soon after, the close of the Pleistocene period. The topography of the islands of the Yasawa group is much younger than that of the coastal hills of Viti Levu across the lagoon. The andesites forming the latter hills are assumed to be contemporaneous with the andesites underlying the sediments of the coastal plain.

These observations suggest that the andesites, extruded after the uplift and folding of the interior sediments of Viti Levu, were eroded, submerged, and overlain by coralliferous limestones and marls throughout the lagoon area; that during the Pleistocene these limestones were warped upward; and that they were then eroded and covered by ash and agglomerate during a more recent (Late Pleistocene or early Recent) period of vulcanism and have since been partly submerged, as shown by the embayed coast lines of the Yasawa Islands.

Outline of the Geological History of Western Viti Levu.

It should be understood that the paleontological evidence from the South Sea islands is so incomplete that the dates assigned to the various events are only approximations. The history, set down in order, is as follows: —

1) An old land of slates and red sandstones was intruded by a batholithic mass which solidified as gabbro, diorite, and granite.

2) The mountain block then formed was deeply eroded and the igneous rocks exposed.

3) Over the eroded surface andesitic flows were poured out.

4) The surface of these flows was deeply eroded and submerged.

5) A coralliferous conglomerate was laid down on the submerged

volcanic rock and, during a period of oscillatory movements, several hundred feet of marls and claystones with occasional thin seams of coal were deposited.

6) This period was followed by one of more decided submergence, during which approximately 150 feet of coralliferous [1] (?) limestone was laid down.

7) The limestones and older rocks were then uplifted, folded, faulted, and eroded.

8) A period of volcanic activity followed, during which andesitic flows and ash buried the eroded sediments.

9) A period of erosion followed.

10) The eroded hills of andesite were submerged along the edge of the island and a series of coastal sediments was deposited.

11) The island was then differentially uplifted and eroded.

12) Post-Glacial outbursts of volcanic activity built up the islands of the Yasawa group and injected dikes into the coastal areas of southwestern Viti Levu.

13) Recent differential movements have uplifted the coasts of Viti Levu and at the same time depressed the Yasawa islands.

EASTERN VITI LEVU.

Having outlined the history of western Viti Levu, the eastern part will now be described and its history compared with that of the western side.

The south-central coast of Viti Levu, between the Singatoka and Navua rivers, is formed of maturely dissected andesites. Sediments of the uplifted coastal plain, usually marls, surround the volcanic hills as far east as Serua Bay, along a coastal strip 25 miles in length. The sketch (Figure 8) shows the uplifted marls near Tangani, where they overlie ash and agglomerate beds and dip 12° to 15° S. E.

The accompanying map (Figure 9) illustrates the topography of the Navua delta plain. This plain is some 10 miles long and 6 miles wide. It is dotted here and there with hills of andesitic rocks. Many of them are so low and so deeply lateritized that they have been leveled by the sugar planters.

---

[1] The writer found no corals in these limestones except in the basal beds underlying the marls. Workers in the Lands Department report corals in place, however, near the head waters of the Navua river, in limestones belonging to this series.

Along the east side of the river near its mouth, mangrove swamps once covered an area of dead coral reef for a mile inland. The dead reef does not rise above the present low-tide level. A considerable period of coastal stability, permitting the river-muds to be built forward over the dead reef for such a distance, is here indicated.

At a point a few miles west of the mouth of the river there are traces of an uplifted sea beach (Holmes, Government Surveyor). Other evidences of recent uplift are seen in the bench levels along the banks of the Navua, 8 or 10 miles from its mouth. The torrential streams, entering the river, flow across small delta flats before they reach the main stream. Eight miles up the river the uplift is estimated to be from 6 to 8 feet. It would appear that the Navua district either stood still or was downwarped during the period in which the coastal plain was uplifted to the west. More recently a slight uplift of the river's delta has taken place.

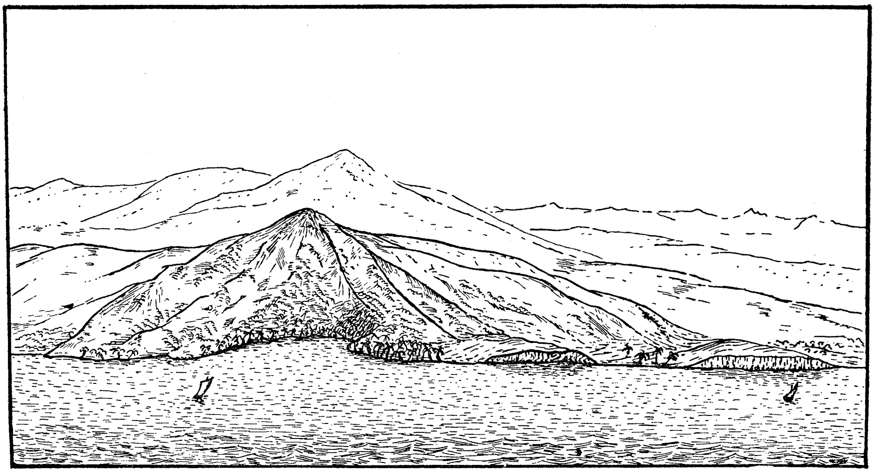


FIGURE 8. View of the Southern Coast of Viti Levu, near Tangani.

The Navua river, like the Singatoka, drains an area in part composed of granites and diorites; hence a considerable amount of coarser material is mixed with the fine clay of the river deposits. In extensive gravel flats, 10 or 12 miles from the river's mouth, boulders of

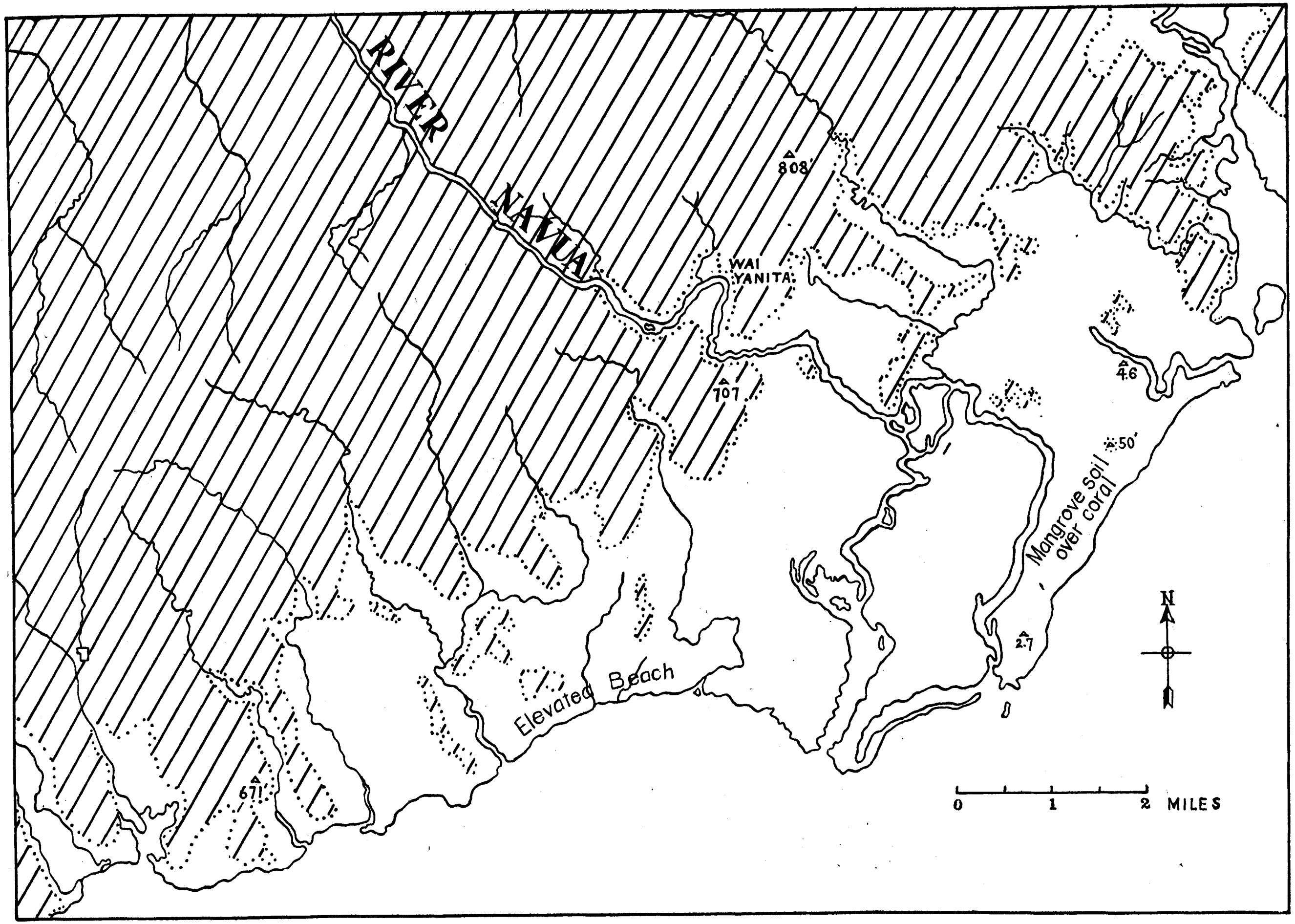


FIGURE 9. Sketch Map of the Navua Delta-plain. White — delta-plain. Lined — volcanic rocks.

diorite associated with sandstone were found. These rocks must be in place not far inland, but lack of time forbade a search for outcrops.

Volcanic rocks, carved into mature hills, form the shore-line for 4 or 5 miles east of the Navua delta plain. An outlying island, Nangara, 10 to 15 feet in height, marks the beginning of the coastal-plain marls. The sediments of the uplifted coastal strip occur at intervals, as jutting points of land or off-shore islands, for 14 or 15 miles to the east, or until the large area of marls forming the eastern side of the island near Suva entirely shuts off the volcanic rocks from the coast.

The short coastal rivers, cutting across the narrow coastal plain, have incised deep, subsequent valleys between the marls and the volcanic rocks just at their contact. This erosion, followed by a slight, recent submergence, has produced a considerable number of off-shore islands. Both processes have rendered it difficult to locate the contact of the coastal sediments with the interior volcanic rocks.

From the island of Nangara eastward, the coastal sediments rise higher and higher on the slope of the volcanic hills until at Tholo-i-Suva, 10 miles from the southeastern side of the island, they are found at an elevation of 700 feet. Along the western part of this strip of land, they do not, however, form the entire coast-line, since a number of the rivers have cleared the marls away from their mouths. The bay-heads usually show outcrops of volcanic rocks, while the projecting points and many of the islands are composed of marl, often interbedded with lenses of coralliferous limestone.

In order to study the relation of the uplifted coastal sediments to the interior volcanic rocks, several trips were made up the small rivers, emptying into Suva Harbor at the extreme southeastern end of the island. All of these rivers cut both the uplifted marls and the volcanic rocks upstream.

At the mouth of the Visari, the westernmost of these small streams, the marls dip 20° N. E. and overlie a conglomerate composed of boulders of diorite and granite. That the conglomerate is older than the surrounding andesite is shown farther up the river, where it disappears beneath a series of andesitic flows. An old rhyolitic breccia is associated with the conglomerate in a way which could not be determined. It is probable that the conglomerate was eroded from the interior granites before the great submergence during which the marl and limestone of the folded series of central Viti Levu were deposited.

The lower course of the Visari is very quiet, but at the contact of the conglomerate and the andesitic flows, 5 or 6 miles from its mouth, huge blocks of the andesite, have tumbled into the stream bed, and falls and rapids abound.

The diorite-bearing conglomerate is not exposed in any of the stream beds east of the Visari. Cross-sections up the Wai-ni-kuta and the Lami, the next streams in order toward the east, show the marls resting immediately on andesitic agglomerates. Up the Tamavua, the most easterly and largest stream entering Suva Harbor, a number of lateritized, maturely eroded hills of andesite are surrounded by marls containing isolated boulders of the same andesites. Along one of the branches of the Tamavua, entering 3 miles from its mouth, an andesite-boulder conglomerate, with a slight amount of marl as a matrix, outcrops. No contacts were seen, but the low dip of the beds and the outcropping of andesitic agglomerates only a short distance farther inland suggest that the conglomerate was eroded from the interior andesitic hills.

Numerous lenticular beds of coralliferous limestone occur within the marls about Suva Harbor. One such bed, 20 feet in thickness, is well exposed in a quarry just west of the town of Suva, on the eastern side of Walu Bay. The contact of the marl with the limestone is transitional. Sandstones overlie the marl and are themselves overlain by conglomerates enclosing broken shells in a calcareous matrix; finally, reef-coral appears. It is thus seen that a bottom composed of coarser shore-detritus is favorable to coral growth.

The coral layers dip eastward at angles of 15° to 20°. These dips may not represent the original angle of deposition, since numerous faults have tilted the blocks of marl and limestone in many directions. Three successive faults have dropped the coral limestone of Walu Bay 45 to 50 feet. The downthrow is always to the northwest. The faulting has given rise to a considerable duplication of the beds and accounts for the irregularity of the limestone outcrop about Suva Harbor. Up the Tamavua river a basal shell-limestone is associated with a calcareous conglomerate which undoubtedly rests on maturely dissected andesitic rocks.

The dioritic rocks of the central core of Viti Levu were not found in place, but they occur in an ancient conglomerate. This conglomerate is overlain by andesite flows, probably of the same age as the andesitic materials overlying the folded and faulted marls and limestones of central Viti Levu. The andesitic flows and agglomerates have been maturely dissected and a series of conglomerates, marls, and interbedded coral limestones laid down about the volcanic terrane, as in the western part of the island. These coastal deposits were later uplifted.

The question remains as to why there is a fringing reef near the mouth of the Singatoka, while off Suva there is a wide and deep lagoon within a barrier reef. The writer believes that two special causes have produced this effect. First, the sediments brought down in abundance by the Rewa river are very fine. They float for a considerable distance out to sea before they are precipitated and are swept by prevailing currents to the westward, along the south shore of the island. The charts show that the reef is indeed fringing east of the river's mouth. The coral is able to grow only beyond the zone of maximum precipitation of the silt. The present barrier reef, therefore, is growing upward on the delta platform of the Rewa river just as the former, uplifted reefs developed in a previous cycle.

Second, the uplifted marls about Suva Harbor present an irregular coast line and an inland topography which cannot be explained by stream erosion. The direct evidence of block-faulting exposed in the Walu Bay quarry is suggestive that the uplift of the coastal marls was accompanied by downthrow and that the lagoon flat of Suva Harbor represents a depressed portion of the uplifted delta.

Comparison of Results with those of Previous Workers.

The history of Viti Levu, as presented above, is somewhat at variance with the older accounts of other geologists. Thus, Andrews describes an unconformity between an older and newer series of limestones at the mouth of the Singatoka river. The coastal plain series at this point appeared to be entirely conformable but, if the writer is correct and intermittent uplifts have characterized the elevatory movements of the coastal plain series, it would not be surprising to find a slight unconformity between an older series of tilted limestones and the very recently uplifted series of coralliferous limestones occurring west of the mouth of the Singatoka river.

A more serious discrepancy is found between the mapping of Woolnough and the descriptions of the present writer. Woolnough does not discriminate between the different marls of Fiji. He mentions the fact that near the mouth of the Rewa these beds are comparatively flat, while near the head-waters of the Navua and Rewa rivers they are considerably folded. This variance in structure, however, is not interpreted to mean a difference in age.

Further, it would appear from his text that Woolnough did not visit the Navua delta plain. He saw the flat country from the hills at the fork of the Navua and Wainikoro-iluva rivers and inferred that it was an elevated plain of marls similar to that near the mouth of the Rewa river. On the contrary, the Navua has incised a series of youthful valleys in a fairly level plateau of andesitic agglomerates. Near the coast, erosion carved the plateau into mature hills, which were later submerged, forming a delta plain about deeply lateritized hills of andesitic agglomerate.

The marl series at the mouth of the Rewa which Woolnough considers Miocene, because of fossils found in the Suva quarries, is believed, therefore, to be much less extensive than is indicated on his map.

In the limited portion of central Viti Levu which was seen, the folded series has a general strike of E. N. E. – S. S. W. as stated by Woolnough. This strike agrees more fully with the structure lines of Suess than with those of Dana or Gregory (Marshall, 1912, p. 3).

Jensen (1907, p. 49) has described an occurrence of chalcopyrite associated with andesite near Lautoka. It may be useful to state that where chalcopyrite was found by the writer it was associated with the older flows of andesite which flooded the eroded plutonic rocks. The folded series of Viti Levu lies above this andesite, which is much faulted and brecciated.

GEOLOGICAL HISTORY OF VANUA LEVU.

INTRODUCTION.

Because of limited time and unfavorable weather, the writer saw less of Vanua Levu than of Viti Levu. The western part of Vanua Levu was not visited, but it is known to be underlain by sandstones and other sediments, similar to those described in central Viti Levu (Guppy, 1903).

PHYSIOGRAPHY.

The outline of Vanua Levu is by no means as regular as that of Viti Levu. The eastern portion of the island is split by a long, narrow bay extending inland, to the southwest, for 50 miles. To the eastern peninsula, thus formed, are appended several minor peninsulas

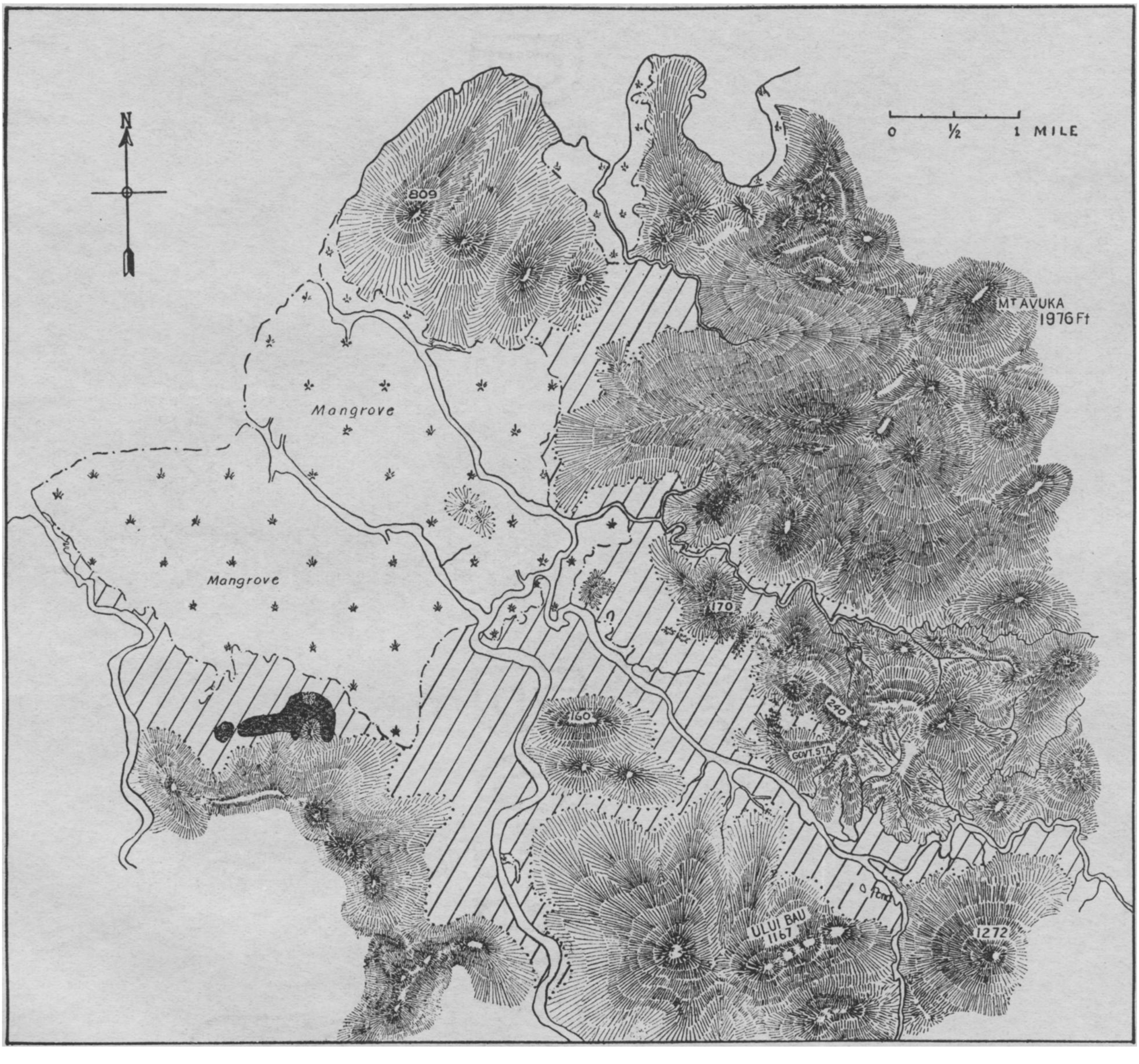


FIGURE 10. Sketch Map of the Lambasa Delta-plain.
Drawn by Wright after a Sketch by Le Roex.
Lined — delta sediments. Black — limestone.

which jut out to the eastward. A few miles off-shore, many small islands further complicate the coastal forms about Vanua Levu. The entire circumference of the main island is marked by pocket harbors and jutting headlands.

The rocks of the island are primarily andesitic ash and agglomerates, though a series of rhyolitic-ash deposits occurs along the northeastern coast. The rocks of the eastern side of the island, deposited subaerially, have never been submerged, and are maturely dissected.

The andesites of the central part of the island are submarine in origin. They once formed a wide, submarine platform of gentle slope, which was later elevated 3000 to 4000 feet and dissected into irregular hills forming a mature to late-mature topography.

LAMBASA DISTRICT.

The low, sugar-cane lands, formed by the delta flat of the Lambasa river, lie a little east of the center of the northern coast of Vanua Levu. The accompanying map (Figure 10) shows the topography of the area. Two tidal rivers, the Nghawa and the Lambasa, have deposited the silts of the delta which is continuous with flood plains far back among the hills. Several residual masses of volcanic rocks stand isolated within these plains, their bases covered with delta sediments (Figure 11).

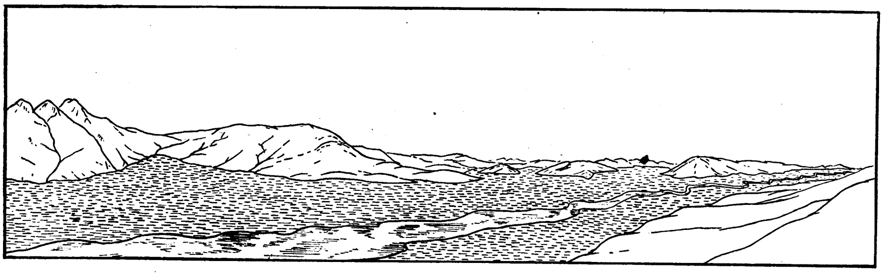


FIGURE 11. View of the Lambasa Delta-plain.
Drawn by Wright after a Photograph.

The region drained by the two rivers mentioned was once occupied by several andesitic volcanoes. The ash deposits which covered the cones were laid down beneath the sea. After later uplift the volcanoes were so deeply eroded that their central agglomerates are now exposed in abrupt cliffs, and the surrounding ash beds have been carved into hog-back ridges. Certain interbedded lava flows were eroded, to form fingering points extending seaward.

Following this period of erosion, the island subsided and coralliferous limestones were deposited about the spur-ends of the hills extending seaward. These deposits have been largely swept away by subsequent erosion. They are known to occur on the northern side of Vanua Levu only at one locality, three miles west of the Lambasa river near its mouth. Here, as shown in the sketch (Figure 12), coralliferous limestones lie in a valley cut in the andesite. The limestone is quite different in appearance from that found elsewhere in the group. It has a paste of light, slate-colored marl. On weathering, the silver-gray of the marl changes to cream-white. A shell-limestone, with occasional small pebbles of andesite, underlies the deposit, while a yellow sandy marl caps it in places.

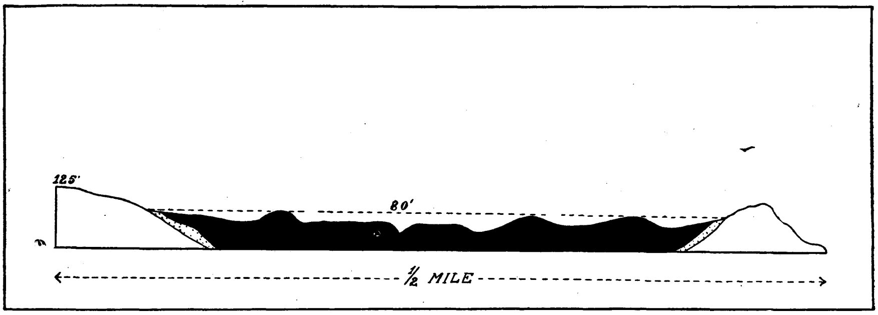


FIGURE 12. Cross-section of an Elevated Coral-reef near Lambasa, Vanua Levu.
White — volcanic rock. Dotted — basal conglomerate. Black — elevated coral reef.

During the period of crustal stability following the subsidence, continued dissection of the andesite produced a series of wide valley floors dotted with residual hills extending far inland. The edge of the central plateau of agglomerates and fossiliferous tuffs retreated farther and farther towards the interior and peaks were carved by erosion from the disappearing mass. The valley peneplain thus formed is now found at an elevation of 125 to 150 feet above sea-level, and may be seen in crossing Vanua Levu from Lambasa southward to Savu Savu Bay on the southern coast of the island. The first part of this journey leads along the flats of the Lambasa river. Then an ascent of 125 to 150 feet brings one to a wide plain stretching inland for 15 to 20 miles. The rocks underlying this plain are largely vesicular, andesitic lava, seamed with chalcedonic veins and containing amygdules of chalcedony and quartz. Calcareous ash-beds also occur. Near the top of the ridge forming the central divide of the island, fossiliferous tuffs are formed at elevations from 2500 to 2700 feet.

The evidence gathered at the coralliferous-limestone exposure led the writer to believe that, following the formation of the valley peneplain, there was an uplift of 80 to 90 feet; then a short period of stability during which a shore platform was cut in the soft limestones. Later, another uplift of 40 to 50 feet allowed valleys to be carved in the shore platform thus formed. Still more recently a rise of sea-level has allowed 10 to 15 feet of volcanic silts to accumulate in these valleys.

A visit to the divide east of the Lambasa plain and southeast of Mt. Avuka (see sketch map, Figure 10) showed that other stages could be recognized in the history of the island. The road winds gradually up from the river flats over a series of low lateritized hills, and then follows the course of a small creek (Na Suvu) which has carved in the laterite a gorge-like valley, 20 to 30 feet deep.

At an elevation of 350 feet, the lateritized materials have been washed away and occasionally the true nature of the rocks may be seen. They are glassy lavas, unconformably overlying maturely dissected gabbro. Ascending still further to the divide at an elevation of 750 feet, the gabbros are lost for a time but appear again along the axis of the ridge. They outcrop for 200 yards along the road as it passes over the divide and, south of the road, rise in a dome 1100 feet high.

On the eastern slope of the divide, pitchstone pebbles are associated with the glassy flow lava which mantles the gabbro surface. To the north, Mount Avuka, 1976 feet in height, is formed of andesitic ash and agglomerate which overlie the glassy flows conformably.

An outline of the history of north-central Vanua Levu is, therefore, somewhat as follows: —

(1) An old land of plutonic rocks was maturely dissected and submerged.

(2) During the great submergence a thick series of volcanic rocks was laid down; first acid flows and later andesitic ash and agglomerates.

(3) A period of uplift followed, during which the submarine tuffs and agglomerates were elevated over 2400 feet (Guppy, 1903, p. 154).

(4) The succeeding period of erosion carved the uplifted volcanic mass into a mature topography.

(5) A period of submergence followed, during which coralliferous limestones were deposited about the spur ends of the mature hills along the coast.

(6) A period of stability allowed wide valleys to be opened in the interior.

(7) A later uplift of 80 to 90 feet was followed by a short period of stability during which a shore platform was wave-cut on the soft limestones.

(8) Renewed uplift of 40 to 50 feet allowed valleys to be carved in the shore platform of (7).

(9) A recent rise of the sea-level has filled the valleys of (8) with volcanic silts.

Northern Coast of Vanua Levu, East of Lambasa.

A rapid trip of 30 miles was made by train, along the northeastern coast of Vanua Levu, east of Lambasa. The rocks exposed are rhyolitic ash and agglomerate. These have been maturely dissected and wide valleys, extending far inland, are found at intervals of 5 to 7 miles along the shore. The coast is very irregular and typically embayed.

The history of this coast appears to be the same as that near Lambasa. During the period in which inland valleys were formed, wave erosion cut into the rhyolitic deposits of many of the volcanic cones along the coast and formed sea-cliffs 300 to 400 feet in height. The friable nature of the rhyolitic ash-beds allowed rapid cliffing. As the cliffs retreated, certain craters seem to have been breached, so that the ocean water entered their floors. The remnants of the crater walls, forming islands and headlands about the bays, show quaquaversal dips.

The floors of the wide valleys of this region stand at a less elevation above the sea than those near Lambasa. Either the uplift, following erosion, was not as great towards the east or, it may be, the depression following uplift was greater. The ocean is now attacking the shore again and carving from the rhyolitic ash a series of undercut cliffs, 20 to 30 feet in height.

MBUTHA BAY DISTRICT.

The Mbutha Bay District constitutes the extreme eastern side of Vanua Levu. The district may be divided into two parts. Between Mbutha Bay and the long, narrow depression forming Natewa Bay, a continuous range of uniform structure and vegetation stretches in a northeast-southwest direction for 50 miles or more. This range has been called, by Guppy, the Natewa peninsula. The island of Kioa, lying a few miles to the east of the mainland and forming part of the enclosing land about Mbutha Bay, has a similar structure, and with a promontory on the southwest, forms a spur of the Natewa Peninsula.

The land at the southeastern end of Vanua Levu, Guppy has called the Waikava Peninsula. The eastern half of this peninsula constitutes the second part of the Mbutha Bay District.

The first-mentioned sub-division of the district, including Natewa Peninsula, is underlain by non-fossiliferous ash-beds, agglomerates, and lava flows of sub-aerial origin. On them, erosion has developed a sub-mature topography. The divide between Mbutha Bay and Natewa Bay is very close to Natewa Bay, so that its northwestern slopes are much steeper than its southeastern slopes. To the east of the divide, along the axis of the range, a number of high-standing basins, a mile to a mile and a half in width, are enclosed on nearly all sides by precipitous walls. The rocks about the basins show quaquaversal dips and the small streams draining the basins issue through narrow openings in the enclosing walls. The basins are, therefore, considered to be old craters.

The river at the head of Mbutha Bay has cut its valley across a series of ash-beds. Its lower course is embayed by a recent submergence, further evidences of which are seen about the shores of Mbutha Bay. Delta-filled valleys abound. The shore-lines of Rambi and Kioa demonstrate the embayment. The accompanying sketch map (Figure 13) shows the coastal outline of the bay.

The killing of coral patches by an advancing delta was observed about the shores. Near the head of the bay, (see sketch map), the coral patches are dead and submerged about one fathom. As the open waters to the north are approached the coral thrives more and more, attaining vigorous growth where the currents sweep in between Rambi and Kioa.

Just east of the small promontory jutting out from the Waikava

Peninsula towards the island of Kioa, the land slopes gradually downward toward a depression which crosses the whole width of the main peninsula. Southeast of the gap, the hills are eroded to late maturity and are deeply lateritized. Their red slopes, overgrown with reeds, are in distinct contrast to the well-watered slopes clad with verdure about Mbutha Bay. This area forms the second part of the district.

The rocks of this district cannot be exactly correlated with those about Lambasa. The andesites of the Natewa peninsula are less dissected than the Lambasa andesites and the interbedded ash gives no evidence of having been laid down beneath the sea. These volcanic rocks are, therefore, probably not of the same age. It may be possible that the more dissected andesites of Waikava Peninsula corresponds to the Lambasa volcanics but most of the rocks of the peninsula are believed to have been erupted since the main uplift of the island.

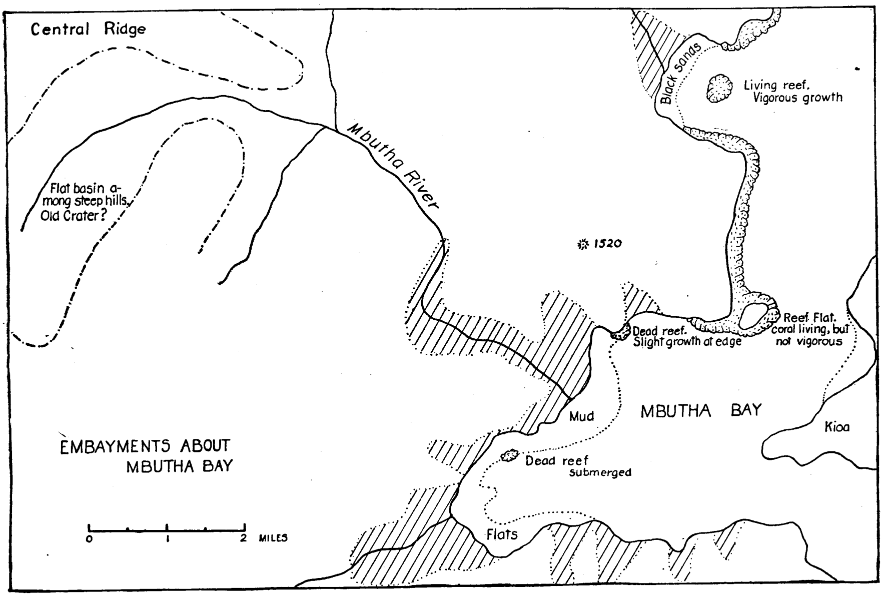

Central Ridge
Flat basin among steep hills, Old Crater?
Mbutha River
Black sands
Living reef. Vigorous growth
1520
Reef Flat. coral living, but not vigorous
Dead reef. Slight growth at edge
Mud
MBUTHA BAY
Kioa
Dead reef submerged
Flats
EMBAYMENTS ABOUT MBUTHA BAY
0 1 2 MILES

FIGURE 13. Embayments about Mbutha Bay, Vanua Levu.

SOUTHERN COAST OF VANUA LEVU.

Only two sections of the southern coast of Vanua Levu were seen by the writer. Each of these was 15 or 20 miles in length and contained areas of uplifted limestone. The first section runs along the southern side of the Waikava peninsula at the southeastern end of the island and extends westward for 5 or 6 miles beyond Fawn Harbor. The second section was made in the vicinity of Savu Savu Bay.

Crossing the Waikava peninsula from the river flat at the head of Mbutha Bay, the land rises to an elevation of 1200 feet within the space of a mile. Near the divide, the peninsula, composed of andesitic ash and agglomerate, presents a sub-mature topography.

As one approaches Fawn Harbor from the east, the highlands of agglomerate retreat gradually from the coast, and a wave-cut bench appears at an elevation of 75 to 80 feet. The agglomerates below the bench level are overlain by fine ash deposits containing some sea shells and a calcareous matrix. The ash unconformably mantles the domes formed by the late-mature dissection of the agglomerates.

A series of islets, composed of ash and agglomerate, cross the mouth of Fawn Harbor. The bay-heads at either side are underlain by loose, fine, volcanic marls, which have been benched by the sea at its present level; the resulting platform slopes seaward at a very low angle (3° to 4°). This platform may be traced for a half a mile out to sea. Just west of the western head-land, the loose yellow and red fossiliferous marls are carved into hoodoo stacks standing 15 to 20 feet above sea-level. For a few miles west of Fawn Harbor, the elevated wave-cut bench extends a mile or two inland. Five miles west of the harbor, near the little village of Vunilangi, the seaward border of the bench has a fringe of raised coralliferous limestone.

The plan and cross-section (Figure 14) show the prevailing conditions. Back of an outer rim of raised coral heads, 10 to 15 feet in height and 100 to 200 yards wide, is a wide flat which was formerly covered by 2 to 3 feet of water. Artificial drainage has made the flat dry and arable. The drain-cuttings show that the plain is underlain by a limestone, composed of shell and coral waste with an occasional coral head in place. A hill 60 to 70 feet high rises in the midst of the flat and represents an isolated dome of andesite unconformably overlain by coralliferous limestone to its summit.

The relations at this place point to very recent uplift. At the time when the sea was cutting, in the andesite, a bench at an elevation of 75 to 80 feet about present sea-level, a reef was forming out to sea on the maturely eroded topography of the andesite. The succeeding uplift has been so recent that none of these features is yet destroyed.

The observations made in the second traverse on the southern coast

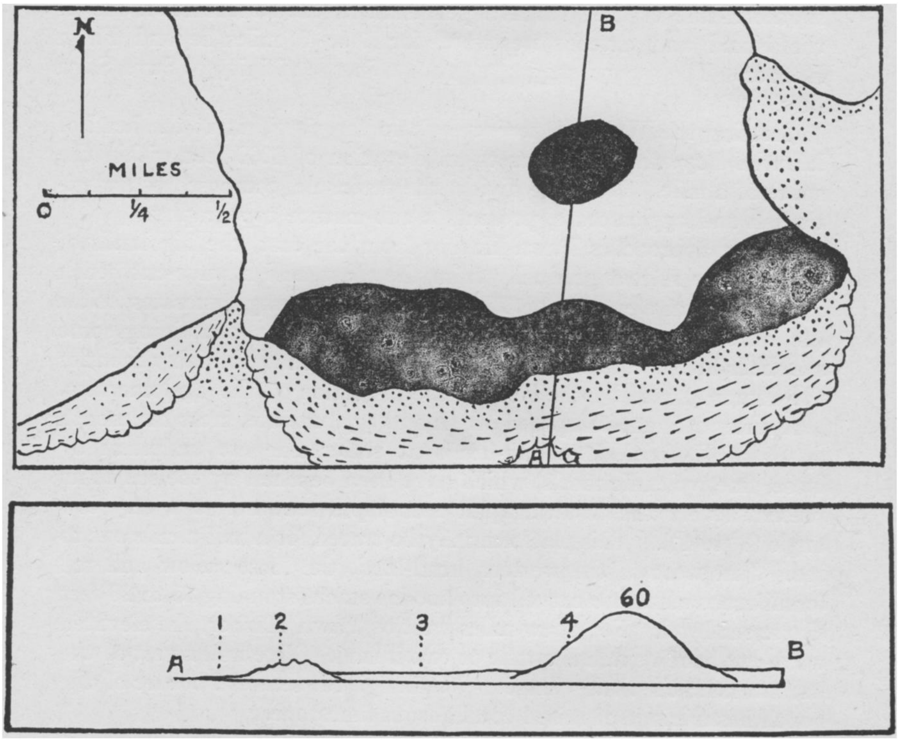


FIGURE 14. Sketch Map and Cross-section of an Elevated Coral-reef near Vunilangi, Vanua Levu.

White — coralliferous lagoon sediments. Black — elevated reef. 1 — Sandy beach. 2 — Elevated barrier reef. 3 — Elevated lagoon flat. 4 — Coral-covered knoll.

may now be noted. Savu Savu Bay is a wide, enclosed sheet of water, reaching 8 to 10 miles towards the center of Vanua Levu. The submature hills overlooking the bay are composed of rocks similar to those found about Lambasa. The lower slopes display andesitic agglomerates and flows. Near the summits of the residual hills, carved from the high-level plateau of the interior, shell-bearing tuffs, interbedded with agglomerates, were found.

There is but one large river flowing into Savu Savu Bay. This river flows from the north and enters the north-central portion of the bay. A few small streams drain the seaward slopes of the ridges, but by far the greater part of the run-off from the back country is carried by a series of subsequent streams into the through-going river. The mouth of the river has flood-plain deposits 4 or 5 miles inland. The tide rises and falls in a tidal estuary, immediately above which the flood-plain deposits cease and the river becomes a narrow torrential stream with a boulder stream bed. There has been a recent submergence of the river's mouth.

Guppy, (1903, p. 182) reports gabbros on the divide between Savu Savu and Natewa Bays. These rocks were not seen by the writer. Their presence indicates at least some similarity in the history of the southern part of the island to that about Lambasa. In both districts, hot springs with temperatures near the boiling point suggests that the areas are now in the expiring stages of volcanic activity.

The most interesting area in the Savu Savu Bay district lies along the sea-coast, east of the eastern bayhead. The present fringing reef seaward from this bayhead is nearly a mile in width. At the western end of the reef there is a small island of elevated coralliferous limestone of lagoon origin. This limestone is lacking for two or three miles eastward from the headland, and a sandy plain extends a quarter of a mile inland to the late-mature, andesitic hills forming the center of the peninsula. Two and a half miles east of the headland and about 200 yards inland, a rise of land called Ndela-ni-koro, is formed of coralliferous limestone overlying a late mature topography of andesite, (Figure 15). The hill is between 110 and 120 feet high. From this point to the village of Nandi, 5 miles east of the bayhead, the tips of the promontories are covered with elevated coralliferous limestone.

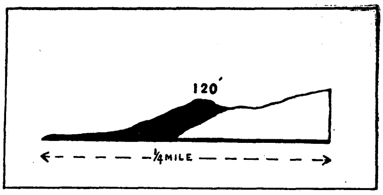


FIGURE 15. Ndela-ni-koro, near Nandi, Vanua Levu.
White — volcanic rock. Black — elevated coral reef.

At Nandi, the eroded andesites were once depressed below the sea, covered unconformably with lava flows which were conformably over-

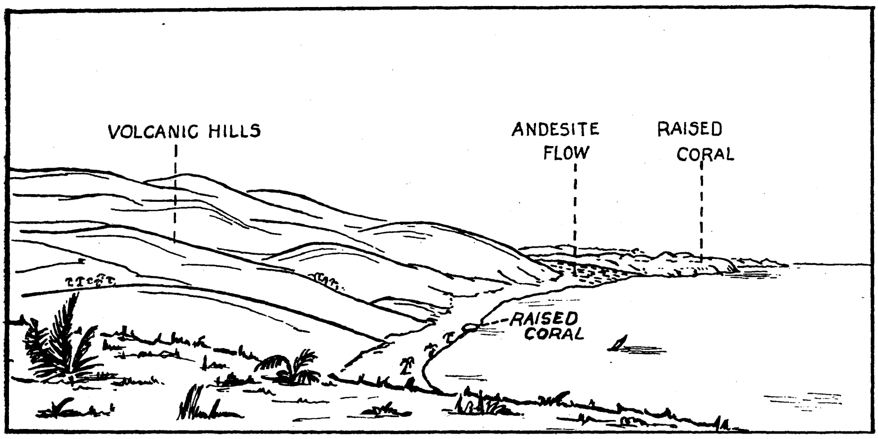
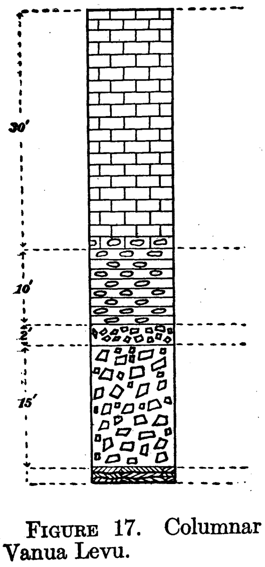


FIGURE 16. View of an Elevated Coral-reef near Nandi, Vanua Levu.



Massive coral heads and rubble-waste in proportion of one to one. Andesitic boulders 1 foot in diameter at base.

Calcareous conglomerate containing coral and volcanic pebbles.

Calcareous agglomerate.

Coarse agglomerate with ash matrix.

Andesitic flow.

FIGURE 17. Columnar Section of an Elevated Coral-reef near Nandi, Vanua Levu.

lain by limestone, and later uplifted. The river, draining the interior, has been extended across the elevated reef limestones. On either side of the bay at its mouth continuous areas of uplifted limestone stretch for half a mile along the coast.

The sketch (Figure 16) illustrates the type of topography near Nandi. The limestone is nearly 40 feet in thickness and dips 3° to 4° S. E. The rocks underlying the limestone are given in the columnar section (Figure 17).

The section indicates that here andesite was erupted during the deposition of the limestone and the other conformable sediments. Farther east no andesite of this relatively late date has been discovered, all the andesites observed being unconformable below the limestone.

TAVIUNI.

The island of Taviuni with its reefs is shown in the sketch map, (Figure 18). Three periods are definitely indicated in the history of the island. They are most easily recognized in its northwestern part, where maturely eroded andesites are surmounted by a number of recent cones, from which basaltic lavas have spread north and east over the adjacent country.

Along the central and northern borders of the island there is an irregular bench, probably cut by wave-action, on the mature and deeply lateritized hills. The bench stands at an elevation of 75 to 150 feet and from it rather abrupt slopes descend to sea level.

Near the west-central coast of the island, recent basalt flows lie within a valley carved below this bench level. The order of events which gave rise to the valley incised in the bench is not clear. The maturely eroded andesites may have been submerged, a bench cut, and later elevated; or the bench may have been cut during a pause in the general uplift of the island.

A continuous northeast-southwest ridge, bearing some of the highest peaks of Fiji, runs through the middle of Taviuni. Near the very center of the island is an old crater whose flat floor is occupied by a shrinking lake. The floor is a mile wide and two or three miles long. It is dotted with two or more small hills which rise from the lake. The crater is rimmed with precipitous cliffs, 200 to 300 feet in height. One of the streams flowing towards the eastern side of the island is said by settlers to breach these cliffs.

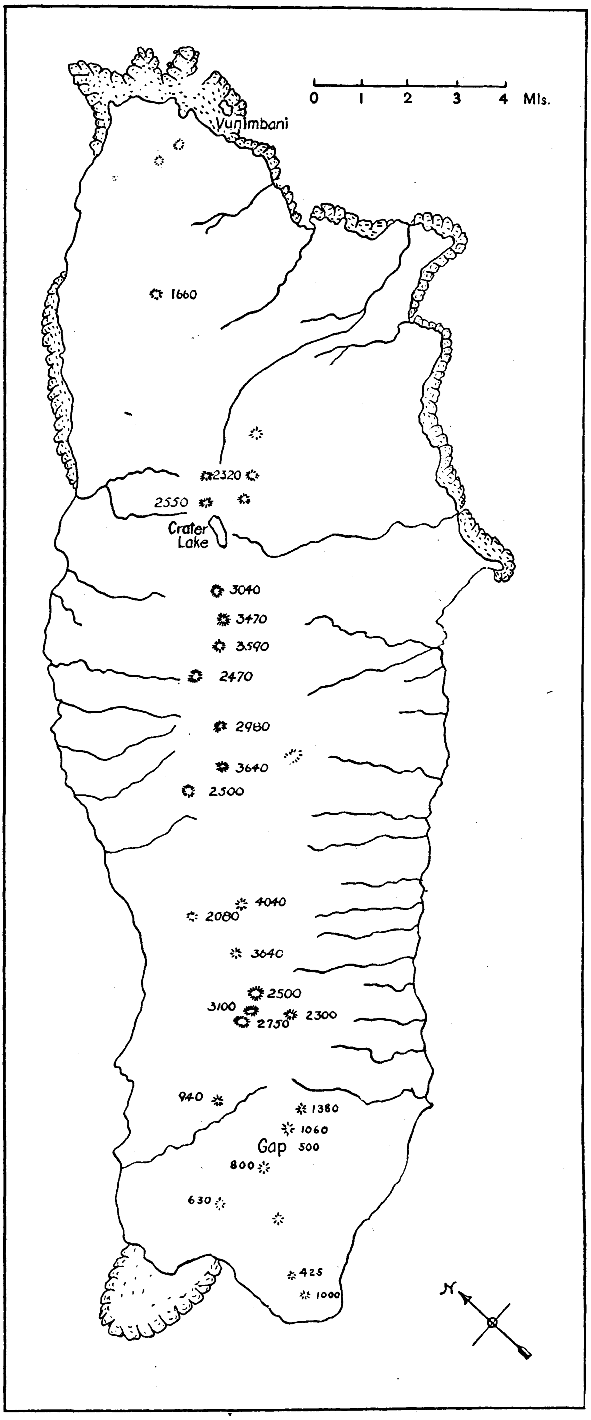


FIGURE 18. Sketch Map of Taviuni.

From the central ridge steep slopes, of 30 to 35 degrees, descend to the sea. The slopes of the central and southern parts of the island are largely underlain by basaltic flows and agglomerate. It is difficult to reconcile the steepness of the slopes with the general fluidity of basaltic lava, if basalts constitute the whole depth of the ridge down to the sea-level. The problem becomes less serious if it be assumed that the basalts actually form a relatively small part of the mass; that is, a veneer on the older andesites exposed at the northern end of the island. In certain places, the basalts present an abrupt change of level as they approach the coast, as though they had flowed out over the bench on the older andesites above described.

At the southern end of the island, a series of seven or eight cones, 700 to 800 feet in height, rise above a nearly flat basaltic plain. These cones are arranged along a north-south line, approximately parallel to the main ridge of the island.

Two different explanations of the isolated reef at the southern end of Taviuni are conceivable. It may represent part of an old reef which was not entirely covered by the recent basalt flows. If so, the depths of 50 to 75 fathoms close to the shore represent the original descent from the edge of the reef into the ocean abyss. On the other hand, the existing reef may be due to the colonization of the flat surface of a recent lava flow extending beneath the sea. The latter hypothesis leaves unexplained the considerable depths close to the land. Block-faulting may account for the sharp descent.

It is easy to postulate faulting in order to explain certain features about Taviuni but difficult to prove it. For example, Goat Island, lying two or three miles off the west coast, is composed of ash-beds which are gently folded and dip towards the basaltic slopes of Taviuni. The present dip would seem to indicate that the source of this ash lay to the west. A deep channel, however, separates the island from Vanua Levu in that direction. It is not impossible that faulting has formed the strait and destroyed the center of eruption from which the ash was ejected. Yet the beds may simply be an erosion remnant cut off from Taviuni.

Again the small island, Vunimbani (200 feet high), off the northeast coast of Taviuni is capped by 15 to 20 feet of water-laid ash, dipping 5° N. E., and overlying flows and agglomerates. The island is connected with Taviuni by a flat exposed at low tide. The coast of the larger island at this point is composed of deeply lateritized basalts whose topography is quite unlike that of Vunimbani.

The accompanying sketch (Figure 19) was made from the northwestern side of Taviuni, looking southward along the coast towards the outlying island of Ngamia. It illustrates the low topography of recent basalt flows which cover the older hills in northeastern Taviuni. It also shows the mature topography of Ngamia and its embayed shore-line. The irregular outline of this island is in distinct contrast to the rather regular outline of Taviuni. If the latter island, like Ngamia, has been submerged, it should also be embayed along its northern shore. The lack of such embayment indicates that either still-stand or uplift has characterized the recent history of the island.

The continuous series of vents along the northeast-southwest central ridge of Taviuni is doubtless located on a fracture-line. Block-faulting along parallel lines possibly accounts for the depths of 75 to 150 fathoms along the eastern and western sides of the island, close to the shore. Yet no evidence favoring this hypothesis is at hand, and the present slope of the modern basalt flows, if continued beneath the sea, would furnish almost as steep a descent to deep water.

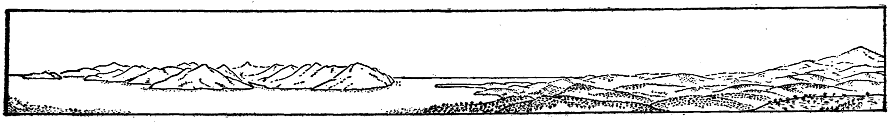


FIGURE 19. View of Ngamia and Northwestern Taviuni from Nangasau.

Besides an intermediate period of uplift, Taviuni, like the district about Mbutha Bay, shows two other distinct periods in its development. The older is that of mature or late-mature erosion and lateritization of andesitic rocks; the younger, that in which more basic rocks were extruded.

The points of greatest importance to be noted in the following table are: —

1) Old cores of plutonic rocks form the centers of both Vanua Levu and Viti Levu.

2) Most of the districts show one period of great subsidence.

3) The submarine volcanic rocks of central Vanua Levu are lacking in eastern Vanua Levu and Taviuni.

4) One period of rhyolitic activity, two periods of andesitic activity, and a later period of basaltic activity are manifested in these islands.

COMPARISON OF THE HISTORY OF VANUA LEVU WITH THAT OF VITI LEVU.

The following table presents a summary of the more important periods in the different districts just described. The periods which are considered to be essentially contemporaneous are indicated by the same numbers.

I *Singatoka River-Viti Levu.*	II *Yasawa Group.*	III *Lambasa-Vanua Levu.*	IV *Mbutha Bay-Vanua Levu.*	V *Savu Savu Bay-Vanua Levu.*	VI *Taviuni.*
1) Plutonic rocks, intruded into slates and sandstones, eroded to late maturity.		Plutonic rocks eroded to late maturity.		Plutonic rocks eroded to late-maturity.	
2) These rocks flooded by lavas of the first period of andesitic eruptivity.		These rocks flooded by rhyolitic and andesitic lava.			
3) Erosion of the andesites.					
4) Great subsidence; deposition of marls, sandstones and limestones of folded series.			Eruption of lava and ash of first andesitic period.		
5) Uplift and erosion of sediments formed in period (4).					
6) Explosive material of second period of andesitic activity covers the sediments.	Eruption of lava and ash of second andesitic period.	Great subsidence; deposition of marine tuffs and agglomerate of second andesitic period.	Eruption of lava and ash of second andesitic period.	Great subsidence; deposition of marine tuffs and agglomerates of second andesitic period.	Eruption of lavas and ash of second andesitic period
7) Mature erosion of volcanoes of second andesitic period.	Erosion of andesites.	Uplift and erosion of the submarine volcanic rocks.	Submature erosion of lavas of second andesitic period.	Uplift and erosion of the pyroclastics.	Late-mature erosion of the andesites.
8) Subsidence; deposition of 100 to 200 feet of coastal marls and coralliferous limestones unconformably on andesites of second volcanic period.	Subsidence; deposition of 300 to 400 feet of limestone.	Subsidence; deposition of 50 to 100 feet of coastal sediments unconformably on maturely eroded andesites.		Subsidence; deposition of coastal sediments.	
9) Uplift and erosion of coastal sediments.	Uplift and erosion of the limestones.	Uplift and erosion of coastal sediments.		Uplift and slight dissection of coastal sediments.	Uplift and cutting of marine bench in the andesites.
10) Intrusion of basalts into coastal sediments.	a. Explosive materials of basaltic period cover sediments. b. Submature erosion of volcanoes of basaltic period.			a. Eruption of lavas of basaltic period. b. Erosion of basalts.	a. Extrusion of basalts. b. Sub-mature erosion of basalts.
11) Submergence (?).	Submergence.	Submergence.	Submergence.	Submergence.	Submergence (?)

GEOLOGICAL HISTORY OF THE SMALLER ISLANDS, ESPECIALLY THE LAU GROUP.

Introduction.

During an extended exploration of the Lau Group which lies to the east of the larger island of Fiji, the writer reached the following conclusions: —

1) The Lau islands are underlain by volcanics, formed during the second period of andesitic eruptivity, then maturely eroded, and finally submerged.

2) During long submergence, coralliferous limestones were laid down unconformably on these volcanic rocks.

3) A later uplift elevated the coralliferous limestones above sea-level.

4) During a later basaltic period of volcanic eruptivity, olivine andesites or basalts intruded the elevated limestones.

5) With succeeding erosion a large amount of the elevated limestones disappeared, largely owing to atmospheric solution.

6) Most of the islands show a recent submergence.

According as the various islands have passed through all, or only a part, of these stages, the Lau islands may be classified as follows: —

I. Islands depressed and covered with limestone and later uplifted and intruded or covered by volcanic rocks of the second period.
  A. Islands depressed so deeply that the tops of the andesitic hills of the first period were covered by limestone.
    1) Islands with limestone partly or wholly eroded from the summits of the andesite.
      Vanua Mbalavu
      Susui
    2) Islands with volcanic rocks of first period still covered with limestone.
      Kambara
  B. Islands whose tops were never covered by limestone.
      Kandavu
II. Islands depressed and covered with limestone and later uplifted but not affected by the second period of volcanic eruptivity.
  A. Islands depressed so deeply that the tops of the andesitic hills were covered with limestone.

1) Islands with limestones eroded partly or wholly from the summits of the andesites.
    - Malatta
    - Avea
    - Thikombia-i-lau
    - Tuvuthá

2) Islands with volcanic rocks still covered with limestone.
    - Vekai
    - Fulanga
    - Ongea
    - Wangava
    - Vatoa

B. Islands whose tops were never covered by limestone.
    - Lakemba
    - Ono-i-lau

III. Volcanic islands of the second volcanic period built on platforms composed of coralliferous limestone overlying depressed hills of the first volcanic period.
    - Munia
    - Kanathea
    - Ono
    - Mbengha

For the purposes of discussion in this paper, the islands are grouped according to a simple plan as follows: —

1) Islands composed of both limestone and volcanic rocks.
    - Vanua Mbalavu,
    - Susui,
    - Lakemba,
    - Malatta,
    - Avea,
    - Ono-i-lau,
    - Kambara,
    - Thikombia-i-lau,
    - Tuvuthá,
    - Kandavu.

2) Islands composed of limestone alone.
    - Vekai,
    - Fulanga,
    - Ongea,
    - Wangava,
    - Vatoa.

3) Islands composed of volcanic rocks only.
    - Munia
    - Kanathea
    - Ono-i-Kandavu
    - Mbengha

GROUP I. ISLANDS COMPOSED OF BOTH LIMESTONE AND VOLCANIC ROCKS.

Exploring Group.

Vanua Mbalavu
Malatta
Susui
Avea
Thikombia-i-lau

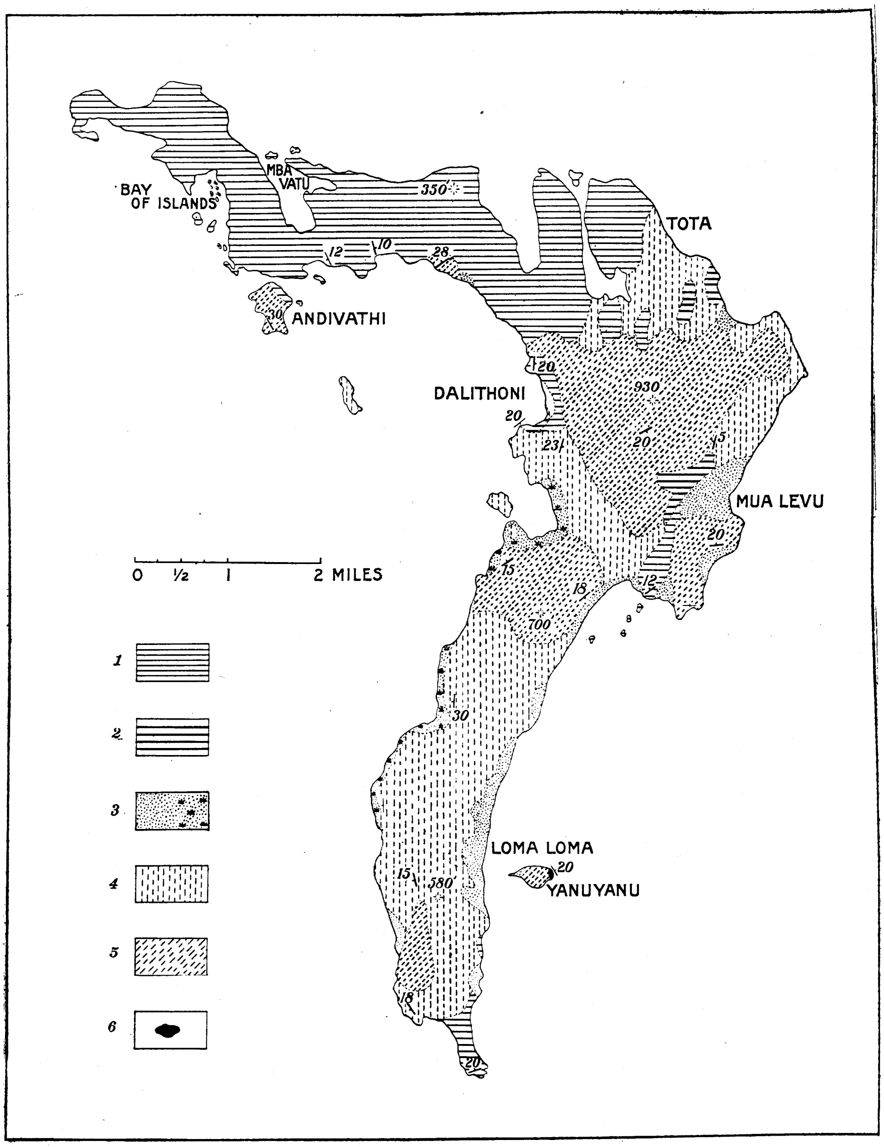


FIGURE 20. Geological Sketch Map of Vanua Mbalavu, Exploring Group.
1 — Coralliferous limestone. 2 — Basal calcareous conglomerate. 3 —Coastal sands and mangrove swamps. 4 — Andesitic lavas of the first period. 5 — Basaltic lavas of the second period. 6 — Ash deposits more ancient than the andesites.

The Exploring Group consists of six large islands lying about the border of a lagoon nearly 30 miles in diameter. All but one of the islands are composed of both volcanic rocks and limestone. The one exception, Munia, consists only of volcanic rocks and will be considered later.

Vanua Mbalavu. The largest island of the group, Vanua Mbalavu, is long, narrow, and shaped somewhat like a question mark. Its greatest length lies approximately in a north-south line. Its extreme northern and southern ends are composed of limestone, while its center is composed of volcanic rocks. As indicated in the accompanying map (Figure 20), the volcanic rocks form the greater part of the island.

The volcanic rocks were erupted in two different periods which will be called the andesitic and basaltic periods of extrusion. The andesites were eroded to late maturity. They were then submerged and coralliferous limestones were laid on them unconformably. Later they were uplifted with the overlying limestones and both were deeply eroded. During the later volcanic period, this eroded topography was buried beneath basaltic flows and ash-beds and the basaltic slopes, in their turn, have been eroded to maturity.

The late-mature hills somewhat south of the center of the island, near the village of Loma Loma, represent the older or andesitic period. They slope gradually to the south from an elevation of 300 to 400 feet, and disappear beneath the elevated coralliferous limestone which unconformably overlies the andesite. A few, very vesicular basalt flows of the later eruptive period occur in the extreme southwestern part of the island, but their source was not found.

Toward the north, at a point near the center of the large curve of the question mark, the slopes of the late-mature hills of andesite continue beneath the limestone. Just south of this point (near Tota) isolated patches of a shell and coral-rubble limestone rest unconformably on the andesite, and further south near the bottom of the curve (Mualevu) other isolated patches lie within a broad valley extending 2 or 3 miles inland. Near the northern edge of this valley, these patches are seen to be overlain by more recent basaltic flows and are colored red, probably due to baking.

Along the sea-coast on the western side of the island (Dalithoni), and near the northern contact of the volcanic rocks with the elevated limestones, there is a series of instructive exposures. A small bay is bounded to north and south by limestone headlands. The southern headland is composed of a foraminiferal limestone containing bits of andesitic ash. The limestone is 30 or 40 feet thick and dips eastward. It may be followed around the bay to the north, but its contact with the overlying rocks is not exposed. It is seen, however, to dip conformably beneath a layer of coralliferous limestone which forms the basal layer of the northern headland. The coral limestone is composed of coral heads in place, with reef rubble between, and is 5 feet in thickness. The coral heads form about two-thirds of the deposit. An agglomerate, 10 feet in thickness, overlies this deposit conformably. The agglomerate consists of large, angular coral-heads which occupy irregular positions, with angular boulders of vesicular andesite, 5 to 6 feet in diameter, fixed in a paste of andesitic ash and lapilli. This peculiar bed is overlain by 15 to 20 feet of a cream-colored coralliferous limestone which in turn is overlain by 20 feet of a pink coralliferous limestone. All the beds are conformable and dip 20° east.

The basal layers of the outcrops just described indicate volcanic activity at the time they were deposited. Yet the upper coralliferous limestone proved to be continuous with the elevated limestones of the entire northern part of the island, and those limestones unconformably overlie the maturely-eroded andesites to the east. Since coral heads in place occur in the northern limestone at an elevation of 350 feet, and also within the mass of the limestone at the bottom of the deposit just described, it is probable that subsidence to the extent of 200 feet, more or less, occurred during the deposition of these rocks.

These relations point to the conclusion that, at the close of the long period occupied by the erosion of the andesites and the development of coral reefs off-shore, new andesitic eruptions broke out, and that soon afterward the island subsided.

The discovery of a limestone layer, underlying later lavas on the eastern side of the island, has already been noted; further evidence of a later extrusive period is found along the northwestern side, within the large curve of the question mark. Flows of vesicular basalt follow the valleys cut in the limestone along this shore.

The small outlying island, Andivathi, is composed of andesitic agglomerates and ash, dipping 30° E. The western beds, representing the lower members of the series, are coarse agglomerate with vesicular blocks of lava, a foot or more in diameter. The upper beds become finer and finer and show many small fragments of pumice. The total thickness of the beds is about 200 feet. The eastern side of Andivathi is composed of elevated coralliferous limestone. Both ash and limestone are cut by a net-work of basic dikes. All the dikes are deeply eroded and their upward extensions are gone. The largest observed dike intruding the limestone is 20 feet in width. It is deeply lateritized and outcrops in a long, well-defined depression in the limestone which forms a perpendicular wall on either side, indicating that the volcanic rock here weathers more rapidly than the sedimentary.

On the northeastern side of Andivathi, ash-beds are seen to overlie the limestone, and to dip southeast towards the eroded and nearly vertical walls of limestone, lying just across a strait, not more than a hundred yards wide.

Again, at Mba Vatu, on the northeastern side of Vanua Mbalavu, thin dikes, about a half inch in thickness, were found intruding the elevated limestone at a height of 300 feet.

Near the center of the large curve of the question mark, a peak, (Koro Mbasanga), 920 feet high, was built up during the second volcanic period and the cone of which it forms a part has since been maturely eroded. This cone has been placed in the second period of volcanic activity, since (1) its lavas are of the basaltic type and unlike the lavas of the first or andesitic period; and (2) lavas traced from this center overlie foraminiferal limestone which rests unconformably on the andesites of the first period.

Scattered over the surface of the deeply lateritized hills of andesite are numerous silicified fragments of coral. It was noticed that the surface waters, carrying silica from the lateritized hills, were apt to deposit the silica near the contact of the limestone with the volcanic rock and it is supposed the silicified coral originated in this way. The presence of the corals indicates that considerable areas of the limestone have been swept away. Whether the andesitic hills of Vanua Mbalavu were ever wholly covered with limestone is not known, but since the elevated limestone now occurs at elevations as great as that of the highest andesitic hills, this is considered possible.

The coastal irregularities of the old andesitic hills, as well as the deep bays of the limestone portion of the island, have been appealed to as evidence of recent submergence. It does not appear to the writer that this evidence is necessarily conclusive. In the first place, the valleys cut in the andesite may have been formed before subsidence and, after the subsequent uplift, uncovered by the erosion of the unconformably overlying limestones. In the second place, the drainage passing from the andesitic hills beneath the limestone or percolating through the limestone to the andesitic contact, has produced effects peculiar to islands of this type. Much of the drainage passes by deep channels out to sea and appears, off-shore, as fresh-water springs. The persistence of these channels has led to the honeycombing of the limestone by immense caves. The roofs of the caves collapse and continued solution, followed by later water-action, create rifts in the nearly vertical walls surrounding a limestone island. The rifts then develop into fringing bays with almost vertical sides, extending far inland. It is believed that the deep bays in northern Vanua Mbalavu have been largely so formed.

Avea. Avea is an oblong island with its longest axis lying nearly northeast by southwest. It is 3 miles long and 1½ miles wide and has an elongated spit of sand to the southwest, as indicated in the accompanying map, (Figure 21).

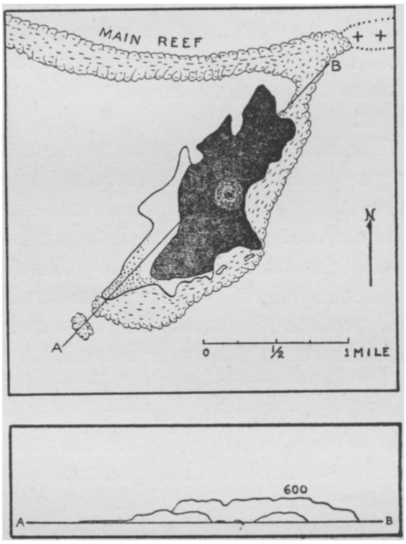


FIGURE 21. Sketch Map of Avea, Exploring Group.
Black — elevated coral reef. White — pyritized tuff. Dotted — sandy beach.

The oldest rock formation of Avea, seen on its northwestern side, is a brecciated, highly pyritized tuff, which was eroded into mature hills. After dissection, these hills were submerged and on them were laid down, unconformably, 310 feet or more of coralliferous limestone. The whole mass was later uplifted and eroded to an irregular island with a sharp, central ridge, with precipitous cliffs of limestone about its shore, except on the northern side, where the tuff is exposed. No exact contact was found between tuff and limestone; yet because the tuff deposits underlie the limestone and rise into it in a series of irregular domes, it is inferred that the history of the island must be as stated. Besides, the pyritization of the tuff must have occurred before the deposition of the limestone, since the latter rock is not pyritized.

Dips of 10° to 14° were seen in the limestones, but, since the limestones of the other islands rise to a uniform level, it is believed they have not been tilted, but rather were deposited at this angle. The same argument holds good for similar irregularities of dip indicated on the map of Vanua Mbalavu.

On the southern side of Avea, coral heads in place were found in small, secluded inlets along the precipitous coast. These heads are conformably overlain by coralliferous limestone. They are surrounded by a paste of coral and shell rubble, as in the present-day reefs. The coral heads indicate that a considerable subsidence must have followed their growth.

Yanu Yanu. The relation of the tuffs to the andesites is not clear from the occurrence at Avea, but is revealed by a study of Yanu Yanu, (see Figure 20). This island is almond-shaped with a sand point extending westward. The island is less than a mile in length and is cone-shaped. Its northeastern side is formed of tuff, visible in a cliff 40 to 50 feet in height. The original form of the deposit has been lost through profound erosion. It now covers an area of less than an acre. To the south the ash is intruded by an acid andesite, which cuts off its further extension in that direction. To the west, the main mass of the island, rising in a cone to an elevation of 270 feet, is composed of an olivine basalt of the second volcanic period, which intrudes and overflows the ash. The presence of these later rocks, surrounding the very loose and easily eroded ash, accounts for the preservation of the latter.

Malatta. The islands of Malatta and Susui, adjacent to Vanua Mbalavu, represent a continuation of the limestone mass forming the southern end of Vanua Mbalavu. This limestone mass has been separated into the three islands by the process of solution and outward drainage outlined above. The process is still continuing and the islands will undergo further dismemberment.

Malatta averages about 200 feet in height. Its interior is so roughened with solution pits that the island is practically impassable. About its shore-line, precipitous cliffs, 40 to 50 feet high, render landing from a boat very difficult. These cliffs break down only near the strait separating the island from Vanua Mbalavu. Just east of the strait, a series of low, late-maturely eroded hills of pyritized tuffs are overlain unconformably by 150 to 200 feet of coralliferous limestone.

Susui. The western end of Susui, east of Malatta, is composed of limestone. The two islands are separated by a tortuous passage, only a hundred yards wide, through which runs a violent tidal current. This portion of Susui is very rough, like Malatta. An inland lake occurs near the passage, which is filled as the tide rises, and the fall of the tide leaves the surface of the lake above sea-level. As a result, the waters from the lake, draining off through underground channels, rise in fountains off-shore within the intertidal zone.

The limestones of Susui rest unconformably on maturely eroded andesite, composing the central portion of the island. The surfaces of the andesitic hills bear silicified masses of coralliferous limestone similar to those found on Vanua Mbalavu, suggesting that the limestone once extended over these hills.

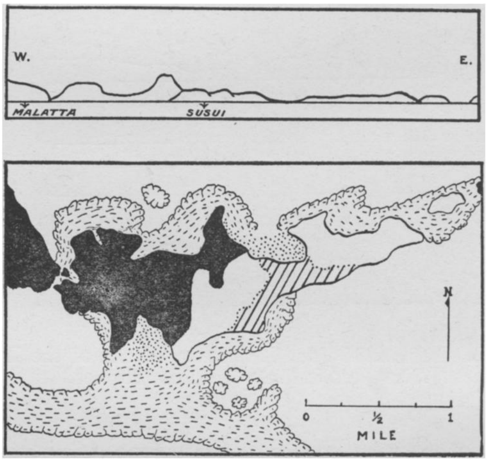


FIGURE 22. Sketch Map of Malatta and Susui, Exploring Group.
Black — elevated coral reef. White — volcanic rocks. Lined — sand flats.

A low sand flat, stretching entirely across the island, connects the andesite with a series of basaltic rocks which form the eastern end of the island, (Figure 22). The basaltic formation is continued in a series of agglomeratic islands extending in a curved line to the northeast. Within the group of agglomeratic islands is one composed of limestone.

The basaltic rocks of Susui and the agglomerates of the outer islands are fresher than the andesitic rocks to the west. The dips of the agglomerates, closely adjacent to the limestone islet, indicate that these beds once surrounded the small island. The directions of dip indicate that the eruptive center lay in the eastern island, Munia. From these facts it is concluded that the basalts of eastern Susui were erupted after the elevation of the limestones of the Exploring group, and thus during the later volcanic period already seen to be important in the history of the group as a whole.

Scattered limestone islets lie within the lagoon, inside the curve formed by the three large islands of Vanua Mbalavu, Malatta, and Susui. On the northern border of the lagoon a few volcanic islands occur. The only other island of any size, except Munia which will be described later, is Thikombia-i-lau.

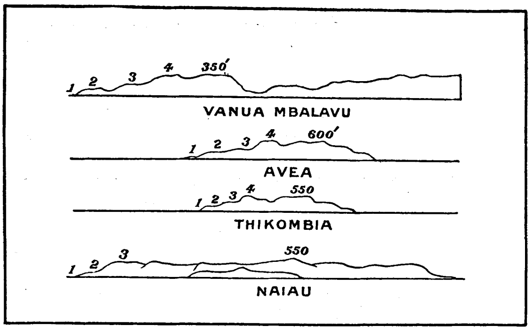


Figure 23. Profiles of Four Limestone Islands of the Lau Group. Numbers indicate possible terraces.

The accompanying outline sketches (Figure 23) were made at a distance from the islands shown, Thikombia-i-lau, Avea, Vanua Mbalavu, and Naiau. Five miles away, one would say immediately that the breaks in the outlines of the islands represent sea-cut benches, yet a closer view causes doubt as to whether they have significance or not. Many of the supposed "benches" represent a chance alignment of several cliffs and hills which cannot be traced with any regularity about the islands.

Thikombia-i-lau. Thikombia-i-lau is shaped like a Scotch bonnet with a central, north-south depression cutting entirely across it. The floor of the depression is formed of andesite; on either side rise coralliferous limestones.

The southwestern side of the island is a mass of andesitic agglomerate, in cliffs 80 to 100 feet high. The contacts of the limestone with the andesitic rocks are difficult to find. At observed contacts no shell conglomerate with inclusions of the andesite was discovered. But, since the limestone overlies large areas of agglomerate and ash and rests on a very uneven surface, it must be inferred that the volcanics were first deposited, later carved into mature hills, and then depressed and overlain by coralliferous limestones. The adjoining sketches (Figure 24) serve to show the areal distribution of the limestone and volcanic rocks and their relation to one another.

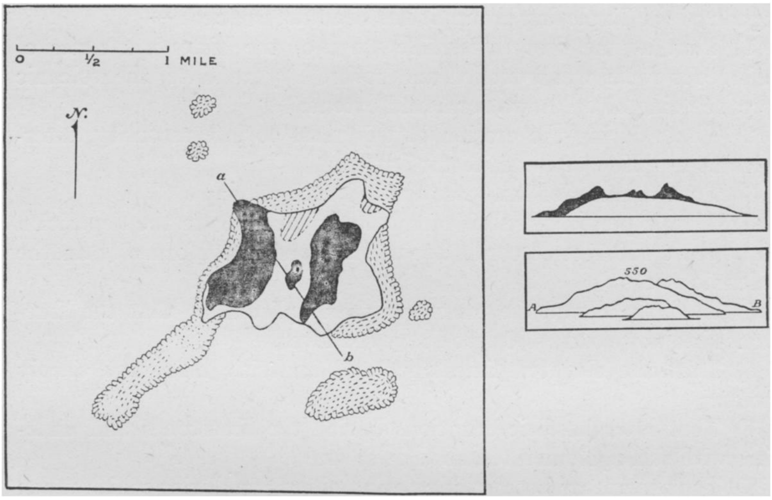


FIGURE 24. Sketch Map of Thikombia-i-lau, Exploring Group.
Black — elevated coral reef. White — volcanic rocks. Lined — sandy flats.

Crossing the island from the small village at its southwestern corner, one first climbs to a bench, 75 feet above sea level. Then follows a steep rise to a second bench at 210 feet, and then a gradual rise to the central valley at 360 feet. The valley is a relatively level floor, a quarter of a mile wide, and extending for a mile or more through the center of the island. Precipitous cliffs of limestone, 200 feet high, rise on either side of the valley.

Though no embayments are indicated in the outline of the island, local, pocket-like, marine plains, formed in the process of coastal simplification, occur about the shore of the island and extend an eighth of a mile inland. These plains are often formed of bedded coral and shell rubble occurring 5 to 8 feet above the present sea level and dipping 10° to 12° seaward.

No definite evidence of the basaltic period of volcanic activity was found in the island.

General Remarks on the Exploring Group.

From the study of the several islands lying about the border of the lagoon of the Exploring group, it has been determined: —

1) That at the first discernible stage of the history, a series of tuffaceous rocks was intruded and covered by andesite, the volcanic terrane being of unknown form and extent;

2) That, during the erosion of this mass to late maturity, intermittent eruption of andesite took place;

3) That this eroded land was fringed with reefs;

4) That a period of subsidence followed, leading to the deposition of at least 400 feet of coralliferous limestone unconformably on the volcanic rocks;

5) That the composite mass was then uplifted, so that the limestones are now found 400 feet above sea level;

6) That the elevated limestones and andesitic hills were deeply eroded;

7) That later basaltic eruptions buried the limestones and andesites with ash, agglomerates, and flows; and

8) That there has been a long period of erosion during which much of the ash and agglomerate of the basaltic period, and much of the limestones, have been swept away.

The existing isolated islands doubtless did not represent the entire land area previous to the great subsidence. It is probable that a series of rhyolitic and andesitic hills once covered an area at least as large as that enclosed by the present lagoon. It was this surface which was submerged and over which was laid down an unknown amount of limestone. Most of the islands studied show that their tops were entirely covered by the limestone and it is inferred that at that time a bank of coralliferous limestone marked this portion of the Pacific Ocean. It cannot be stated whether the bank had the form of an atoll. Some of the higher volcanic peaks of Vanua Mbalavu may have risen above the surface of the bank, but the indications are that the andesitic hills were entirely covered by limestone. The submerged surface of this bank may or may not have been as flat as the present lagoon floor. The irregular surface of the sunken land would, initially at least, involve considerable variations in the depth of water on the shoal.

Subsequent elevation brought great masses of the coralliferous limestone above the sea. Much of this limestone has been swept away by atmospheric solution and wave erosion, as is shown by the isolated islets of limestone dotting the present lagoon. The depths within the lagoon and the distribution of the limestone remnants suggest the possibility that the present andesitic hills represent only the high points of the older topography; that the uplift only served to shallow the depths over the bank and not in all parts to elevate its surface above sea-level; and that the subsequent basaltic eruptions and long continued erosion have furnished material with which the lagoon floor has been smoothed.

During uplift the coral would continue to grow about the edge of the elevated limestone mass. When uplift ceased, the destruction of the limestone by atmospheric solution and wave cutting would go on apace. If these limestones were not protected by a reef during the Glacial epoch, they must have been rapidly eroded. Certain it is that the elevated coralliferous limestones have disappeared from the edge of the present reef and only isolated remnants remain within the lagoon.

The depths between the isolated patches of elevated limestone are exceptionally great when compared to the average lagoon depths. They reach 90 to 100 fathoms at the eastern border of the lagoon, depths too great to have been produced by wave-cutting. Submarine solution cannot be postulated for reasons which are well expressed elsewhere, (see Vaughan, 1914, p. 27; Daly, 1915, p. 231; Davis, 1914, p. 576). Submergence furnishes the only valid explanation.

Direct evidence is lacking on the question whether this submergence was due to actual subsidence or to a rise of the ocean level after the Glacial period. The re-distribution of the loose volcanic products emitted during the basaltic period of eruptivity, and the erosion of the basaltic cones to maturity have furnished material sufficient to level the lagoon floor to a considerable degree. Even today the lagoon floor has an exceptionally irregular topography but these irregularities may be residuals of the eroded topography of the andesites. Portions of the lagoon are fairly flat and the question arises whether this flatness has been induced by sedimentation, by wave-cutting, or by both. The lack of pronounced embayment of the basaltic islands, suggests that most of the period during which the basaltic cones were eroded to maturity has been one of comparative still-stand, yet there is no evidence that this period has been sufficiently long to level the lagoon floor.

The outstanding fact remains that the present barrier reef is developing on the remnants of a bank of coral limestone once elevated and eroded, and now submerged.

Tuvuthá.

The general features of Tuvuthá, about 20 miles south of the Exploring Group, are similar to those of Thikombia-i-lau. Precipitous limestone cliffs surround the island on nearly all sides. The accompanying map and cross-section (Figure 25) show the distribution of limestones and volcanic rocks, and their relation to one another.

Only for a short distance along the northwestern side of the island are volcanic rocks known to outcrop at sea-level. The highest peaks on the island are of limestone. The greater portion of the interior is a rough, heavily vegetated, limestone country eroded into weird forms by solution.

Descending the steep limestone cliffs by tortuous ravines covered with thick undergrowth, one is suddenly confronted by a barren andesitic ridge, lying in the center of the island. The ridge is half a mile wide and about a mile and a half long. It is deeply lateritized and, at the time it was visited, bore no vegetation because of drought. The ridge, 540 feet high, is surrounded by a circular moat. Outside the moat rises a continuous cliff of limestones. Limestone patches also overlie the andesite of the central ridge.

Tuvuthá, like Thikombia-i-lau, was formed by the mature erosion of an isolated volcanic peak. It was then submerged, overlain by limestone, and uplifted. The occurrence of olivine-basalts in a conglomerate near the sea-coast, and the irregularity of certain limestone-andesite contacts suggest that a second period of volcanic activity affected the island after its uplift, but full evidence for this conclusion is not forthcoming.

The contact of the limestone with the volcanic rocks of the interior shows the surface of the andesite to undulate in low, rolling hills.

The unconformably overlying limestone is shelly, and of a red color, because much impregnated by iron. The rain descending on the central volcanic hills is led away by underground channels along the contact of limestone and andesite. No rivers occur on the island. Only one fresh-water spring was found. This appears near sea-level at the contact of the limestone with the andesite, on the northwestern side. This method of drainage causes the replacement of the limestone by many of the elements carried in solution from the volcanic hills.

No pebbles of the underlying andesite are found in the shell limestone. However, the contact is considered to be unconformable for three reasons; (1) there is no evidence of thermal action of the andesite on the limestone; (2) the contour of the andesites beneath the limestones is that of maturely eroded hills; and (3) the texture of the andesite does not become finer near the contact.

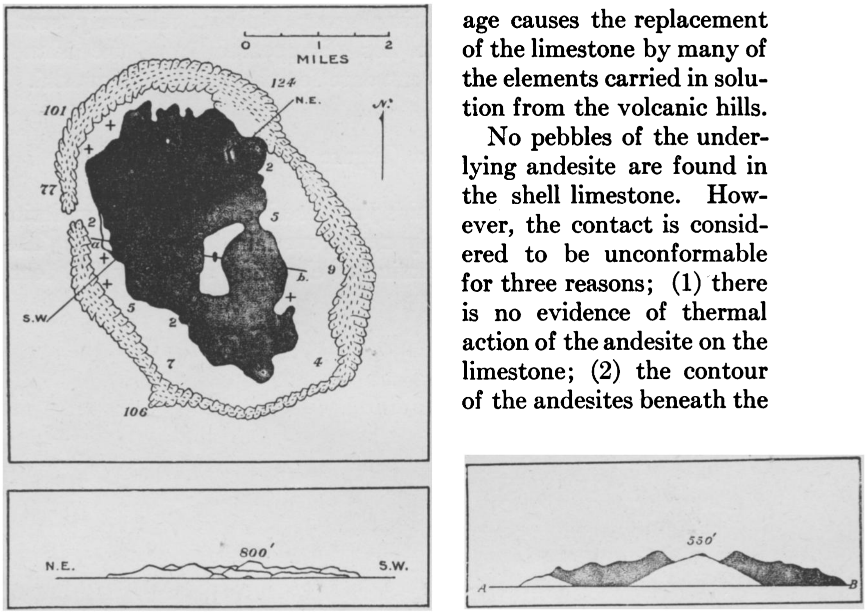


FIGURE 25. Sketch Map and Profile of Tuvuthá.
Black — elevated coral reef. White — volcanic rocks.

The contact of limestone and volcanic rock on the northern side of the island is less conclusive. It is true that a volcanic breccia, cemented by calcite, underlies the limestone and indicates erosion previous to subsidence, but elsewhere the contacts are so dike-like that it is difficult to imagine how an eroded surface could assume such forms. Reviewing all the evidence, however, it is concluded that the limestone, throughout the greater part of the island unconformably overlies the andesite.

Coral heads in place appear from top to bottom of the 590 feet of limestone; and in such relations that subsidence is the most logical explanation of their position. However, the greater part of the limestone is coral and shell rubble which surrounds occasional coral heads.

The depth of the lagoon about Tuvuthá is 6 to 8 fathoms, much less than the average depths of the lagoons of the Exploring group. As compared with the Exploring group, only a relatively small amount of upraised limestone has disappeared from the island. These facts suggest a more recent date for the uplift of Tuvuthá.

Lakemba (Figure 26).

Lakemba differs from the islands just described, in that the andesite forming its center was probably never overlain by limestone. The volcanic surface, reaching a maximum elevation of nearly 800 feet, is composed of well-rounded, mature forms. The rocks are deeply lateritized and support a scanty vegetation. The only fertile spots on the island are found along the lower portions of the stream courses, whither the best of the soil from the volcanic hills has been transported; or at the heads of the bays, where the coral sands produce an abundant coconut harvest.

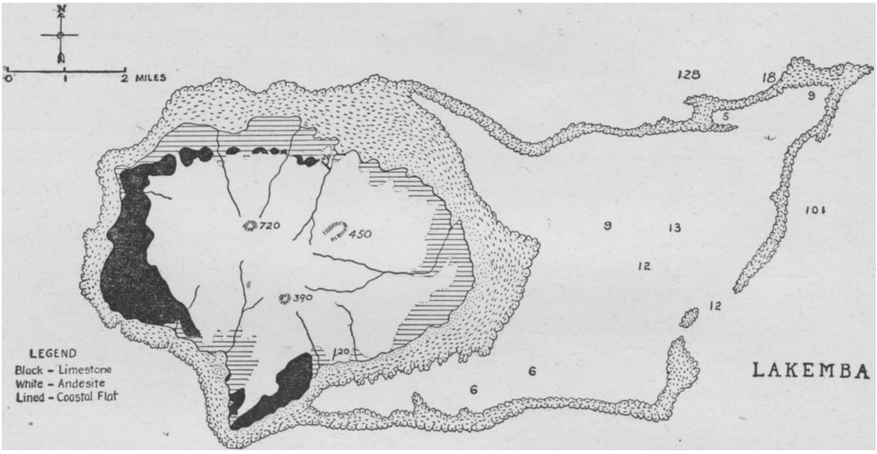


FIGURE 26. Sketch Map of Lakemba.

Along the boundary of the volcanic area are isolated remnants of elevated limestone which once encircled the island. Such remnants unconformably overlie the andesite and rise to a maximum elevation of 320 feet. A castle-shaped mass, with the height mentioned, occurs on the northwestern coast. A mile east of this locality, spur-ridges and their intervening valleys are covered with a mantle of shell and coral rubble mixed with volcanic pebbles up to an elevation of 100 feet. The diagram (Figure 27) illustrates the position of the limestone with respect to the andesite. The average dip of the contact between the andesite and the limestone is 18° N.; the dip of the conglomerate is 12° N.

Following along the coast to the southwest, the conglomerate sweeps inland and, toward the sea, is overlain by coralliferous limestone. The contact between the two deposits is transitional, as may be seen by tracing the conglomerate from its inland contact with the andesite to the coralliferous limestone cliffs near the sea. The same fact is revealed in the sea-cliffs; their lower portions are often formed of shell and coral waste bearing volcanic pebbles and passing upward into reef-limestone.

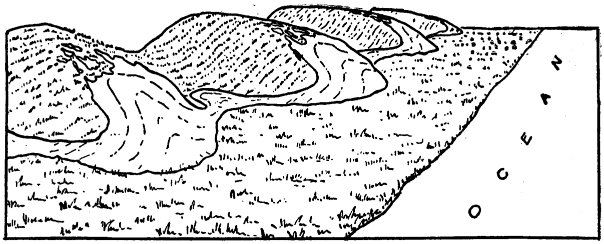


FIGURE 27. Sketch of Spur-hills, Northern Lakemba.

Peculiar drainage conditions obtain here. Descending the mature valleys carved in the andesite of the interior, one would naturally expect to reach the coast easily. In some instances this is true, but usually a wall of limestone, 75 to 100 feet high, cuts across the valley. Beneath the wall the surface waters run down amidst a collection of boulders swept from the andesite hills, and flow to the sea by underground channels, truly remarkable caverns. Many of the cavern roofs have collapsed, affording open passage-ways to the sea. To the southward the passage-ways have been widened until mere remnants of limestone tip the ends of the spur-ridges.

Thus, the island, bearing a number of andesitic cones, underwent mature erosion and subsided. The mature topography was not entirely submerged, since 400 feet of the island still remained above the sea. The sunken portion was overlain by 320 feet, or more, of coralliferous limestone, and was later uplifted.

The limestone remnants decrease in altitude along the coast towards the east and do not occur throughout the eastern third of the island. The disappearance may be explained in two ways. It may be due to more rapid solution on the rainy side of the island or it may be due to tilting during uplift. If erosion were the cause, it would seem that the rainy side should show a more mature topography than the dry side. It is, however, significant that the western side shows greater erosion than the east.

Again, the reef on the western side of Lakemba is narrow and fringing, but on the northeast it sweeps far out and includes a lagoon 8 or 10 miles wide. The width of the eastern reef suggests that it has either been long established or recently submerged. The western reef on the contrary appears to have been established in sub-recent times. Recent valleys cut in red clay at the southwestern side of the island support this conception, whereas the drowned valleys of eastern Lakemba indicate a tilting in that direction.

In this connection it is important to note that the Lakemba lagoon has a maximum depth of 14 fathoms; the Aiwa lagoon, 4 miles to the southeast, 21 fathoms; and the lagoons of the Argo reefs, 15 miles to the east, depths of 20 fathoms on their western side, of 35 fathoms on their eastern side. These depths are greater than the average for the Lau islands and may be attributed to the eastward tilting movement described above, (see table II, p. 93).

An outline of the geological history of Lakemba is as follows: —

1. Period of volcanic activity.
2. Period of erosion, carving to maturity the volcanic peaks formed in the first period.
3. Period of subsidence, during which 4 to 5 feet of conglomerate, 15 to 20 feet of shell sandstone, and 300 to 325 feet of coralliferous limestone were deposited unconformably on the andesitic surface.
4. Period of uplift in the western part of the island accompanied by tilting toward the east.
5. Period of erosion.

Ono-i-lau (Figure 28).

The accompanying chart presents the main features of the Ono-i-lau group. Near the center of the circular lagoon, about 6 miles wide, lie three large islands. These are arranged about a central depression which represents an eroded crater. The crater walls have been breached and dissected, their remnants being the islands, Ono Levu, Ndavura, and Ndoi. They are composed of interbedded andesitic ash, agglomerates, and flows.

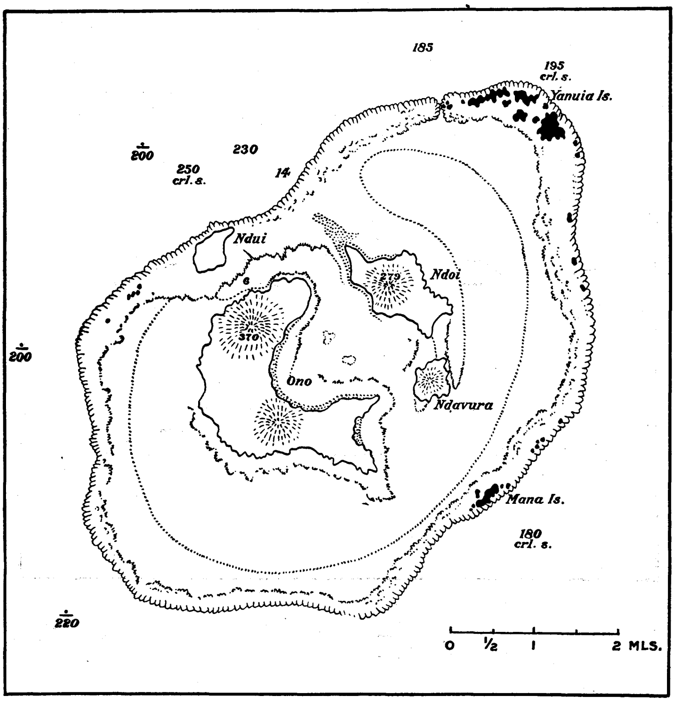


FIGURE 28. Sketch Map of Ono-i-lau.
Black — elevated coral reef. White — volcanic rocks.

About the border of the lagoon, close to the edge of the present reef, are groups of elevated limestone islets. The group at the northern border is known as the Yanuia islands; that at the eastern border, as the Mana islands. Elsewhere about the border, isolated toadstool islets appear; on the western side of the lagoon in the lee of the largest island (Ono Levu) a sand island, Ndui, has been built up.

Ono Levu represents the southern third of the old crater wall. It is crescentic in shape and at either end stand two flat-topped hills, between which there is a low sag. The flows and agglomerates composing the island dip outward from the central depression. They are cut by a series of dikes which radiate from the old crater.

The island has a low, rolling topography of late-mature hills of deeply lateritized andesite. Erosion goes on rapidly during heavy rains; the water runs from the hills in sheets rather than in streams, sweeping off layers of the lateritized soil.

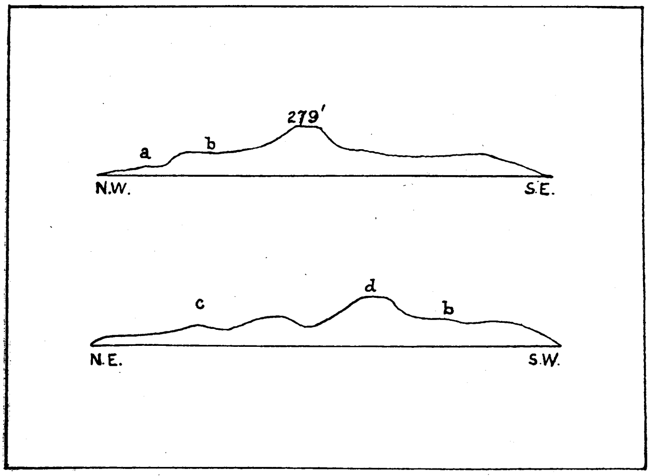


FIGURE 29. Profiles of Ndoi, Ono-i-lau.
a — Sand flat to leeward. b — Lateritized andesite flat at 100 feet. c — Hogbacks of andesitic flows. d — Central butte of agglomerate.

Ndoi shows outward dips and mature topography like Ono Levu. On its northern side a few hog-back ridges are composed of relatively resistant lava flows between the softer ash-beds. A well defined wave-cut bench surrounds this island at an elevation of about 100 feet. Though present in the other island, the bench is there not so well preserved. These features are illustrated in the outline sketches (Figure 29). On the eastern side of Ndoi the sea has cut in the agglomerates a platform 100 to 300 feet wide, at the present sea-level. The width of the bench indicates a crustal stability of some duration.

Yanuia, Mana, and other limestone islands about the border of the lagoon are largely composed of reef material in place. Coral heads often form 50 per cent of the visible limestone. The elevated limestone with its surface now 15 to 20 feet above sea, has been greatly etched by solution, with the generation of thousands of sharp points which make the surface nearly impassable. The dips of the limestone as taken on the Mana Islands were 18° and 11° S. and on the Yanuia Islands 15° S. E. Since there is no evidence of tilting in the group, these dips apparently represent original angles of deposition.

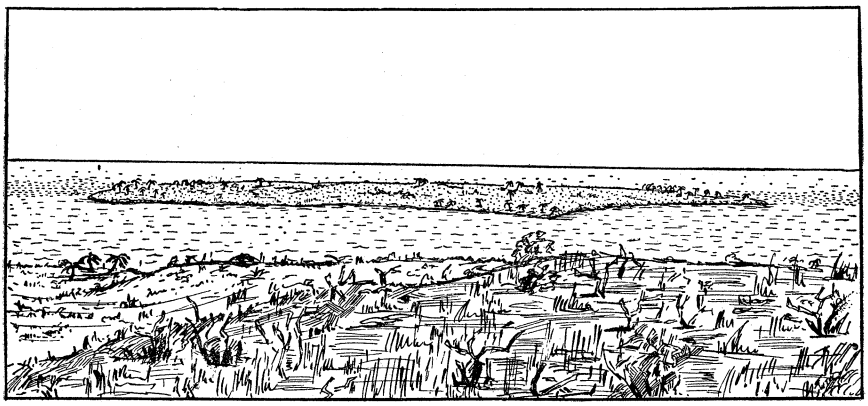


FIGURE 30. View of Ndui from Ono Levu.

The recurrence of the limestone islets at intervals about the edge of the reef seems best explained on the assumption that they are remnants of a more or less continuous mass of limestone, which has been largely destroyed and on which the present barrier reef has developed. Though no solid limestone is exposed in Ndui (Figure 30), the close proximity of limestone islets suggests the presence of a limestone basement beneath the sand. The prevailing easterly winds sweep the sand from the eastern side of the lagoon around the volcanic islands, and pile it against the western reef at its inner border, in the lee of the volcanic islands. Practically no coral grows in the lagoon near its western side. Sand flats, fordable at low tide, extend from the island out to the reef.

The Ono Group presents many similarities to Totoya, lying to the northwest, except for the lack of uplifted limestones in Totoya. The crater wall of Totoya is breached in only one place and is not broken into separate islands, as at Ono. The old crater of Totoya has an average depth of water of 28 to 29 fathoms, while the lagoon depths between the reef and the volcanic islands average 18 to 20 fathoms. This contrast is reversed at Ono, where the maximum depths within the crater are 6 to 8 fathoms and those in the outer lagoon are 8 to 10 fathoms.

The topography of Ono is of a type showing this island to be older than Totoya. The longer erosion has tended more completely to fill the crater depression with silts from the volcanic hills, as well as with debris from the eastern reef.

The 100-foot bench on Ndoi, already noted, may be correlated with the uplifted barrier reef and possibly the surface of the reef has been reduced by erosion from 100 feet to 10 or 15 feet in the period since the uplift. If so, the reduction of the lagoon depths by 100 feet, would be an important factor to consider in accounting for the present shallow water about the islands.

The Ono Group presents a good opportunity to compare known facts with theory. The remnants of elevated coral limestone stand approximately at the edge of the present reef. If the limestone originated in pre-Pleistocene times, they were elevated either before, or after, an inferred period of Pleistocene wave-cutting. If they were elevated before, it would seem that wave-cutting should have destroyed these evanescent forms near the edge of the reef. If they were elevated after the Pleistocene, barrier reefs, accepting the postulate that the corals are of pre-Pleistocene age, must have existed in pre-Pleistocene times; for the ordinary agents of erosion would hardly destroy the inner parts of a fringing reef and leave the outer in the form of a barrier reef. But the Glacial-control theory conceives that the existing barrier reefs and atolls are special forms of coral growth, developed on platforms cut in the Glacial epoch, and that they were much rarer before that epoch than at present.

However, the elevated limestones may have developed not in pre-Pleistocene but in Pleistocene or Recent times. It is possible that a bench was formed about the Ono Group by Pleistocene wave-cutting; that a barrier reef grew up about the islands, with the return of the waters after the Glacial epoch; and that, later, the barrier reef was uplifted.

If this hypothesis be true, a number of events must have occurred since Pleistocene times. There must have been a period of still-stand during which the barrier reef was formed and a bench cut in the volcanic rocks of the central islands. This period was followed by one of uplift. Since then, the inner bench has been largely destroyed, the elevated limestones reduced from 100 to 10 or 15 feet, and a bench, 100 to 300 feet wide, cut in the volcanic rocks at the present level. The rapidity of subaerial erosion in the South Sea islands allows the writer to believe that such a series of events is not impossible in the time postulated.

If the barrier reef were formed by subsidence according to Darwin's theory, it would be important to know the amount of the subsidence. The prevailing slopes of the volcanic flows interbedded with the agglomerates today, average between 12° and 15°. The barrier reef, in developing from a fringing reef, would probably not build itself up vertically, but as this method of formation would give the maximum value for the subsidence, the calculation will be made on this basis.

The barrier reef is now on an average 1½ miles from the volcanic hills. A fair average of the slope of the original hills would be 15°. From these data the maximum amount of subsidence is calculated to be approximately 2000 feet. The outward growth of the reef and the erosion of the central volcanic hills would tend to reduce the figure for the subsidence; so that the actual subsidence necessary to produce the present barrier reef by Darwin's theory would be well under 1500 feet.

That Ono should subside 1500 feet is not at all incredible in view of the great subsidence of the larger islands; yet this hypothesis involves the nearly complete filling of the lagoon.

The persistence of frail islet masses of uplifted limestone, near the edge of the Ono reef, forces one to the conviction that the waves are very impotent just behind a barrier reef, and that their cutting cannot have significantly enlarged the present lagoons.

Kambara (Figures 31 and 32).

Kambara offers one of the most puzzling problems found among the smaller islands. It is an oval mass of limestone, 6 or 7 miles long, 3 to 4 miles wide, and surrounded by precipitous cliffs on nearly all sides. An irregular ridge, about 200 feet high, follows the nearly circular shore-line. The inner slopes of the ridge converge toward the center of the island, where the elevation approximates 80 feet. The limestone mass is therefore basin-shaped. The seaward cliffs are usually unscalable. Access to the interior of the island, is however, possible by way of local solution pits in the limestone. The interior is honeycombed with pits and caverns. Here and there a flat area of an acre or so is covered with a red, residual soil on which the natives grow coconuts. Some of the caverns extend below sea-level and in them the tide rises and falls.

On the seaward face of the enclosing ridge there is frequently a bench at an elevation of 100 to 125 feet. The general dip of the limestone forming the cliffs at the northern side of the island is 10° to 12° outward. The rock is composed of coral heads in place (forming nearly 30 per cent of the whole) and coral and shell rubble. Corals in place were found within the dissected mass at sea-level. There is no evidence of a volcanic substructure in Kambara even within its low interior basin. It is believed, therefore, that the visible island essentially represents a single mass of limestone, in places 350 feet high. There is no structural evidence that the coral-liferous limestone is a veneer on older Tertiary limestone. The observed attitude of the bedding shows the limestone to be everywhere conformable and of low dip. The conclusion follows that the island was formed by subsidence.

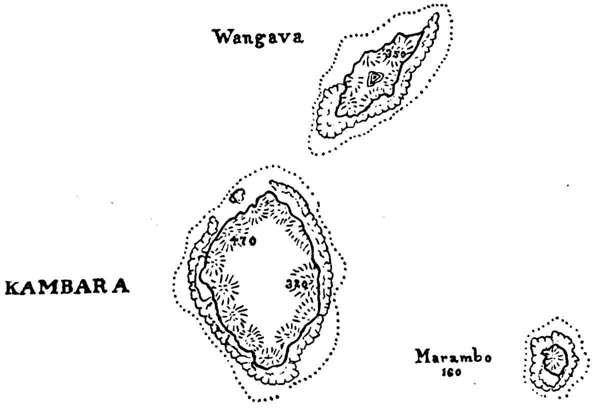


FIGURE 31. Sketch Map of the Islands of Kambara, Wangava and Marambo.

The main puzzle of the island is connected with its volcanic rocks. Although no igneous-rock basement is exposed, a hill, Ndelai Yaloi, 350 feet high, at the northwestern corner of the island, has been found to be composed of basalt, rich in olivine. J. Stanley Gardiner, (1898, p. 464) states that the "basalt, which has apparently welled out from a fissure near the base of the limestone cliffs — gradually increased in height, so as finally to overflow them and form a high hill."

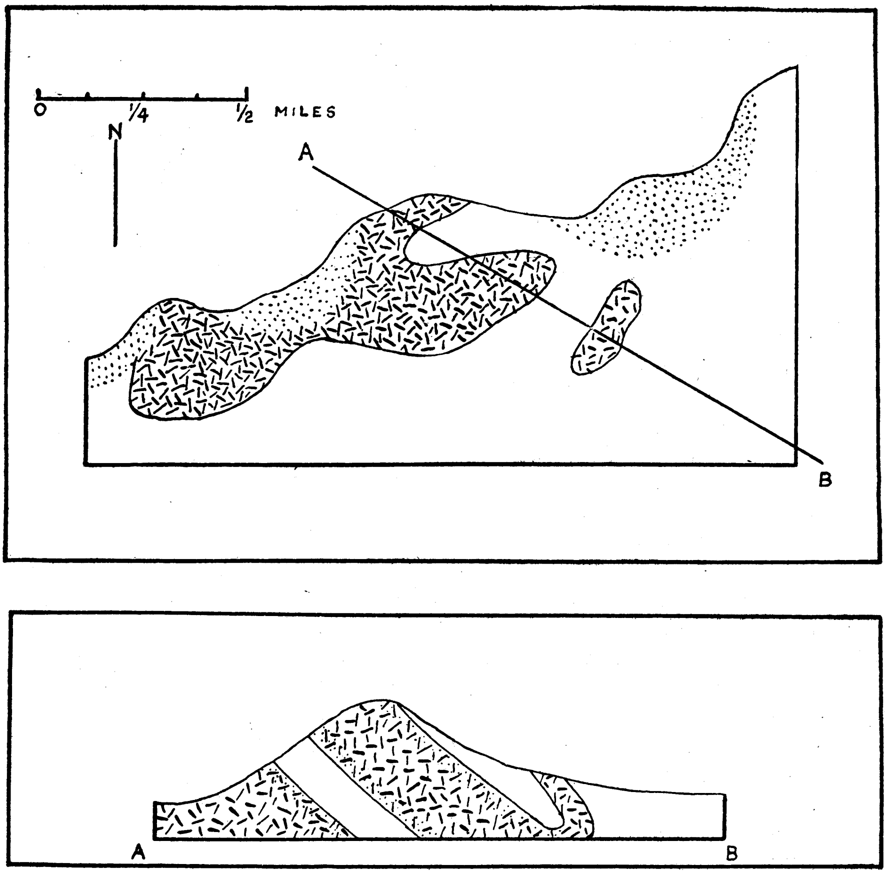


FIGURE 32. Sketch Map and Profile of Ndelai Yaloi, Kambara. White — elevated coral reef. Dashed — intrusive dike of basalt. Dotted — sandy flats.

The author studied the basaltic body (see Figure 32) and concluded that it was a dike, but saw no direct evidence of out-welling flows. The summit of the hill represents the outcrop of the dike. The coarsely vesicular character of the mass would indicate that the injected mass was here close to the surface. The dike is the more remarkable for this very fact. It is 250 to 300 feet thick, strikes about N. 70° E. and dips 55° S. E. It may be traced for 600 to 700 yards along the northwestern side of the island. Limestone was seen on both hanging wall and foot wall. There was no evidence of contact alteration of the limestone. The vesicles of the contact basalt are large and very fresh-looking. If they had even been subjected to water circulation below the sea-level, they would probably have been filled with calcitic or chalcedonic amygdules, but they were found to be entirely empty. The freshness of the rock as a whole and the absence of amygdules point to the probability that the dike was intruded later than the uplift of the island.

The question arises whether the dike magma ever reached the surface. The dike projects as a lone ridge, the highest point on the island, and dips away inland, presenting a steep escarpment to the sea. The face of the escarpment is the continuation of a very straight line of limestone cliffs forming the northern side of the island. It is believed that the surface outflows from the dike, if they ever existed, are invisible because faulted beneath the sea. The down-faulted block includes a small, northern sector of the original island, measuring about one mile in length and a quarter of a mile in width. The faulting postulated is suggested by: —

(1). The regularity of the northern face of the island across both limestone and volcanic rocks.

(2). The existence of a parallel escarpment on the adjacent island of Wangava.

(3). Depths reaching as much as 150 fathoms at points close to the shore.

(4). The abrupt termination of the barrier reef on the east and the west.

(5). The improbability that the long scarp is a wave-cut cliff, since it is situated on the leeward side of the island and since a distinct wave-cut bench at the foot of the scarp is lacking.

It appears, therefore, that after the uplift of the island, the dike was intruded and then the island was diminished by down-faulting on the north.

The reef about Kambara is fringing for most of its length, but has the barrier relation on the northeastern and northwestern sides of the island, where it projects as two short horns.

The writer's general impression is that the island has been elevated quite recently. The fringing reef is regarded as a simple outgrowth about the edge of the elevated island. The barrier reef at the northeastern and northwestern sides of the island may be connected with subsidence connected with the down-faulting of the northern side.

GROUP II. ISLANDS COMPOSED WHOLLY OF LIMESTONE.

Introduction.

A considerable number of islands show outcrops of limestone only. It is reasonable to suppose that in each case, volcanic rocks exist at no great distance below the surface and have not been uplifted above sea-level or, if so, have not been exposed by erosion. The presence of sideritic veins cutting the limestones, veins probably deposited by hot-spring action, tends to support this view. Kambara, the island just described, lacks exposure of its volcanic basement, but its limestone has been intruded by basalt; this relation is an exception to the rule that most of the islands which show large masses of limestone without an exposed volcanic substructure, have not been affected by the later period of volcanism.

What forms characterized the limestone masses before they were uplifted? Were they atolls? This question will be discussed after the facts concerning the islands, described by some as elevated atolls, are stated.

Wangava (Figure 31).

Wangava is one of the least dismembered of all the limestone islands visited. Naiau presents similarities in form, but this island was only seen at a distance.

The following sketch of Wangava (Figure 33) as seen from the northern shore of Kambara, illustrates its flat aspect, visible from practically any direction. The writer visited only the northwestern side of the island.

Wangava is 5 or 6 miles in diameter. It is surrounded by an elevated rim with precipitous cliffs about the coast. Its interior is basin-shaped and marked by numerous pits and caves similar to those of Kambara. The island has another feature not seen at Kambara, a central lake, three quarters of a mile across. The tide rises and falls in the lake about which toadstool islets of limestone stand and steep cliffs 75 to 100 feet in height rise about its edge. The depth of the lake varies. Near its shore and for some distance out it is only 4 to 5 feet deep and its bottom is covered with a black vegetable mold. In places, however, the bottom cannot be seen. From statements made by the natives the average depth near its center appears to be 3 to 4 fathoms.

There are many underground caverns about the edge of the lake and certain of these undoubtedly connect it with the sea. At one point on the northern side, there is a depression in the rim of the island and the limestone beneath is shattered, though there is no wide opening. The depression is probably due to the collapse of a cavern roof.

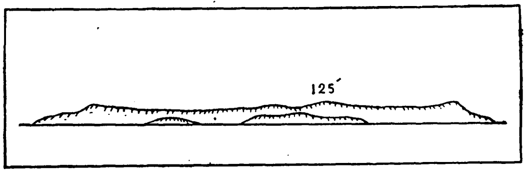


FIGURE 33. Profile of Wangava as seen from Kambara.

The limestones collected show that re-crystallization has gone on extensively near the center of the island and to a smaller degree near its edge. Sideritic veins and pockets abound. The limestone is composed mostly of coral rubble and shell waste. In fact no good examples of coral heads in place were seen, even in the rim of the island.

As already noted, the northwestern shore of Wangava has a fault-scarp parallel to the one described in Kambara. There are depths of 100 fathoms close to the shore; no reef exists on this side of the island and the coast-line is very regular. It is inferred that the fault which affected Kambara, affected Wangava also.

The narrowness of the fringing reef about the other sides of the island suggests, as at Kambara, the recency of the establishment of the present shore-line, presumably by uplift. If a platform had been cut during the Pleistocene period, the recency of the uplift would imply that this bench should now be above sea-level since the island has been uplifted 350 to 400 feet, an amount greater than the supposed rise of the ocean due to the return of Glacial waters. The upper surface of the island could alone represent the Pleistocene platform, for only minor benches are found about the edge of the island above sea-level. If the island represents an atoll which developed on a Pleistocene bench, the bench must be above sea-level according to the Glacial-control theory. In this case the Recent atoll must be assumed to have completely welded itself upon an older limestone mass; for no evidence of unconformity was found.

Ongea (Figure 34).

Ongea differs from Wangava in representing a later stage in the dismemberment of an elevated mass of coralliferous limestone. Two islands lie within the lagoon of Ongea. The southern one, Ongea Ndriti, was not visited. Ongea Levu has a wide, fingering bay indenting its southern side, which is transformed into a sand flat at low tide.

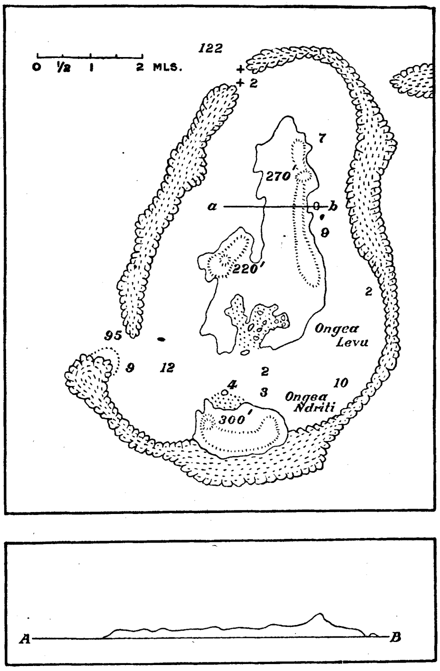


FIGURE 34. Sketch Map and Profile of Ongea.

This flat is covered with toad-stool islets whose overhanging ledges are 4 to 5 feet above the surface of the flat and project 8 to 10 feet from the main body of the rock.

As shown in the accompanying sketch map and cross-section (Figure 34) a narrow, steep-sided ridge, 270 feet in height, runs along the eastern side of the island. A dismembered ridge, 220 feet high, is located on the extreme western side. Between the ridges there is a flat, pitted plain, dotted with caves. The roofs of the caves bear stalactites and often one portion has collapsed, leaving the other portion as a niche in the side of a cliff. East of the seaward base of the eastern ridge, a flat 500 feet wide occurs at an elevation of 10 to 15 feet above sea-level.

There exists, therefore, in Ongea a flat, central plain at a slight elevation above the sea which has been produced largely by atmospheric solution. If the ocean level should rise but a few feet, this plain would be converted into a region similar to the sandy plain at its southern border. Neither atmospheric solution nor wave-erosion within a lagoon can, however, produce a level surface of this type 10 to 11 fathoms below sea-level. In other words, the present lagoon about Ongea must have been submerged since its formation. As the elevated corals are Pleistocene or Recent in age, it is believed they were uplifted in post-Pleistocene time, and hence the lagoon flat about the island cannot be ascribed to Pleistocene wave-cutting, nor the depth of the water above the flat to the rise of the ocean after the melting of the Glacial ice. A recent period of subsidence is, therefore, inferred.

Vatoa (Figure 35).

Vatoa, or Turtle Island, is an isolated mass of limestone lying 50 to 60 miles south of the Ongea Group. The single island within the reef resembles Ongea Levu in structure, as is shown by the following cross-sections (Figure 35). There are high ridges on the eastern and western

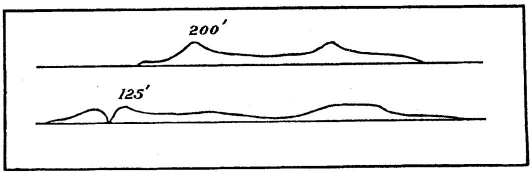


Figure 35. East-West and North-South Profiles of Vatoa.

sides of the island and between is a low, pitted plain. A sea-cut bench at an elevation of 10 to 12 feet is well defined along the northeastern side, but disappears to the south, where its absence may be due to more active atmospheric solution or to a tilting of the island. An extensive sand flat projects southward as a long reef-point which would perhaps suggest that the latter view is correct.

Dismembered portions of the elevated limestone mass of Vatoa dot the lagoon about the island. They have largely disappeared from the eastern coast, probably because of the greater abrasive efficiency of the lagoon sands to the windward. In the western lagoon they are found within 300 yards of the edge of the barrier reef.

The northern end of the island is in process of dismemberment from the southern part. A strait 20 to 30 feet in width separates the two remnants. This strait is bare at low tide and the basin-shaped depression near its center contains a pool filled with small coral heads.

There is no good passage across the reef at Vatoa. The anchorage is a protected bay in the reef to the westward. In rowing across the reef flat and lagoon to the main island a generalized section was drawn which holds good for most of the reefs studied (Figure 36).

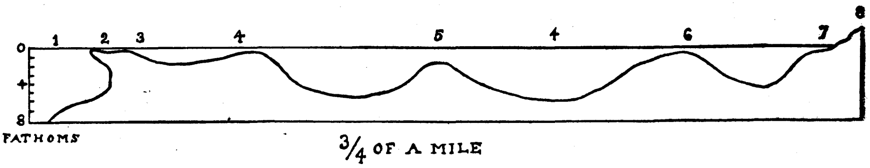


FIGURE 36. Typical Cross-section of a Barrier Reef.

(1). Sandy platform at an average depth of 7½ fathoms with some coral waste.

(2). Overhanging ledge of honeycombed coral through which are openings looking down into the depths. Mushroom heads of coral.

(3). Holes in the coral formation are here filled with sand. Coral growth is less abundant and stag-horn coral prevails.

(4). The sand increases in amount till the flat is nearly barren of coral and in the lagoon only an occasional head is seen.

(5). Coral patch with fairly vigorous growth of rounded heads.

(6). Bar connecting toad-stool islets; coral growth is here vigorous.

(7). This zone varies with conditions. If the lagoon is wide and the sand, carried back across the barrier reef, settles before it reaches this zone, a fringing reef develops; otherwise a sandy bottom is found.

(8). Elevated bench of coral and shell debris cast above high-tide level and often cemented into well-bedded limestones. This bench usually gives evidence of seaward growth.

Fulanga (Figure 37).

The island of Fulanga lies a few miles to the west of Ongea and 80 to 90 miles south of Lakemba. Within an encircling rim of elevated limestone lies a beautiful bay of islands for which Fulanga is noted. These undercut islets of varying sizes number from 300 to 400. The boat passage giving entrance to the bay is but 80 yards wide and one or two fathoms deep. Through it passes a strong tidal current, making the entrance very difficult even for small boats.

The surrounding rim of limestone is breached at several places along its northeastern portion, but elsewhere it is continuous. Forming the backbone of this rim is a ridge 125 feet to 250 feet in height with precipitous cliffs on its inner and outer sides. These cliffs are dotted with niches, the remnants of collapsed caves still festooned with stalactites.

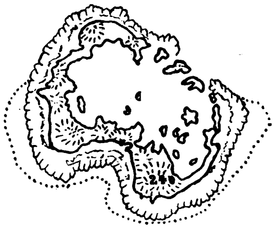


FIGURE 37. Sketch Map of Fulanga.

The small islets within the bay vary in height. The larger are 150 feet high; the smaller, because of undercutting and solution, rise only a few feet. Between the islets the depths vary from 1 to 6 fathoms and at one place somewhat west of the center of the bay, 10 fathoms is recorded. J. Stanley Gardiner, (1898, pp. 457 and 471) has referred to the island as an elevated atoll, but as in the case of Wangava, the central depression may be due to the more rapid erosion in the center of an elevated coral bank.

The writer visited the outer side of the rim along its western shore. Sand flats extend well up to the foot of the retreating central ridge.

At the foot of the cliffs lie abundant blocks of the limestone, fallen from the collapsed caves in the cliffs. As might be expected, the limestones here are greatly recrystallized. No large masses of coral heads in place were seen.

On the inner side of the rim, along the northwestern horn, sandflats lying 3 or 4 feet above high-tide level finger into the base of the central ridge. About the flats are many pinnacles of limestone. A slight submergence would allow undercutting to progress and the pinnacles would be transformed into islets similar to those dotting the central bay.

Where evidence could be secured, the cliffs at this side of the rim appear to be largely composed of material like that in the cliffs of the outer rim (coral and shell rubble). But at one place, back of the village of Navindamu, a lense of coral heads in place, 5 or 6 feet thick and 150 to 200 feet long, is clearly discernible. At the base of the deposit, which lies 10 feet above sea level, are 2 to 3 feet of sandy débris containing bits of shell and coral, loosely cemented. This bed is overlain conformably by 4 to 5 feet of coral-head limestone. A paste of the underlying, sandy deposit fills the interspaces between the heads. None of these deposits was cemented, while overlying them were 150 feet of much re-crystallized limestone, so compact that its texture can barely be made out. An occasional fragment of coral or shell is discernible; otherwise original structures have been obliterated.

The dips of the limestone taken at several points along the inner and outer side of the rim are 8° N., 10° N., 5° E., and 12° N. No evidence of tilting was seen in the island, and it is inferred that these dips represent the original angles of deposition.

The present reef is fringing for the greater part of the circumference of the island, though shallow lagoons, slightly over a fathom in depth, occur at intervals. The continuous shifting of sands within the inner bay makes it a poor habitat for corals, and few develop there. The sand is also a factor in the under-cutting and slow destruction of the central islets.

Much of the reasoning with regard to the origin of the islands of Ongea and Vatoa applies to Fulanga. The depths of the central bay indicates submergence. The narrowness of the surrounding fringing reef points to a recent shift of the sea-level. Atmospheric solution has so far dismembered the island that only a part of its rim now remains, together with an occasional bit of its center, over which the water is now, in general, 6 to 10 fathoms deep.

Vekai.

The island of Vekai represents almost the final stage in the destruction of an elevated bank of coralliferous limestone by atmospheric solution, the transformation of the resulting platform into an atoll by submergence, and the upgrowth of corals about its edge. Vekai reef is slightly over 2 miles in diameter. No portion of its rim has been aggraded above sea-level. On its eastern edge three or four remnants of a dismembered island of elevated limestone rise out of the ocean. None of these remnants is over 15 or 16 feet in height and their combined area is less than an acre. The limestone is so re-crystallized that nearly all its original structure is lost. It is extremely brittle, rings under the hammer and contains a considerable amount of magnesia. The surface of the islets is so rough and jagged that walking is dangerous. A few more centuries of undercutting and solution will destroy them completely.

Group III. Volcanic Islands.

Introduction.

Between the large islands of Viti Levu and Vanua Levu, and the Lau Islands on the east lies a group of purely volcanic islands, namely, Koro, Mokongai, Wakaya, Mbatiki, Nairai, Ngau, Moala, Totoya and Matuku. None of these islands was visited. Koro was seen from a distance and appeared to have certain resemblances to Taviuni. Several of the islands of the Lau group are wholly volcanic. The largest of these are Kanathea, Munia, Olorua, Mothe, and Komo. Only Kanathea and Munia were visited.

Of the islands more or less closely associated with Viti Levu and Vanua Levu, Ovalau, Mbengha, Kandavu, and the Yasawa group are mainly volcanic. Of the Yasawa group, Yasawa-i-lau alone is composed of elevated limestones. Though previously unknown, it was found that the volcanic rocks of a part of Kandavu are underlain by limestones.

The stay on Ovalau was so brief that little geological work was possible. The island appeared to be a volcanic cone in a sub-mature stage of erosion.

The islands to be described are the following:— Munia, Kanathea, Mbengha, and Kandavu.

Munia.

Munia is the one remaining member of the Exploring group not described. It differs from all the others in that it has no limestone in its composition. The island belongs to the last or basaltic period of volcanic activity and is believed to have been built on an eroded bank of elevated coralliferous limestone and volcanic rocks.

Munia is elliptical in shape, its main axis directed northeast-southwest. It is composed of interbedded layers of agglomerate and ash which have been deeply eroded. A central ridge, 950 feet high at its summit and flanked by retreating cliffs, runs northeast through the island. The ash-beds exposed in the face of the eastern cliffs dip 20° to 30° E. In the rainy season land-slides from the cliffs are not infrequent. The slopes at the northeastern side of the island, are gentle and follow the initial dip of the volcanic rocks. At the extreme northeastern end of the island the deposits are nearly all ash.

On the southwestern side of the island, a depression appears to represent an old crater. Along its inner slopes the dips of the volcanic beds are quaquaversal and slope in every direction except to the north and northwest, where the crater walls have been destroyed. In describing Susui, an adjacent island, it was stated that the eastern end of that island is formed of agglomerates which dip westward and had their origin in Munia. Remnants of the original western slopes of Munia are also to be found as dismembered islets about the lagoon. The following map and cross section (Figure 38) illustrate the type of land form developed in Munia. The eastern slopes are clearly erosional forms but probably the western side of the island was destroyed by explosive violence, merely supplemented by erosion.

The volcanic débris, erupted from the crater in Munia and now composing the eastern part of Susui, overlies elevated limestone. For this reason Munia has been placed in the recent or basaltic period of eruptivity of the Exploring group. The recency of the volcanic action is attested not only by the topography but also by the slight lateritization of the basaltic agglomerates. While lateritization has extended to a depth of 20 to 30 feet in the andesitic rocks of Vanua Mbalavu, the maximum observed depth in Munia is but 2 or 3 feet.

The shore-line of Munia is little indented and gives slight indication of recent submergence. On the contrary, a recent uplift is suggested by the fact that some floors of the mature valleys are trenched by small streams to depths of 5 to 8 feet.

The formation of a volcano on an eroded mass of elevated limestone

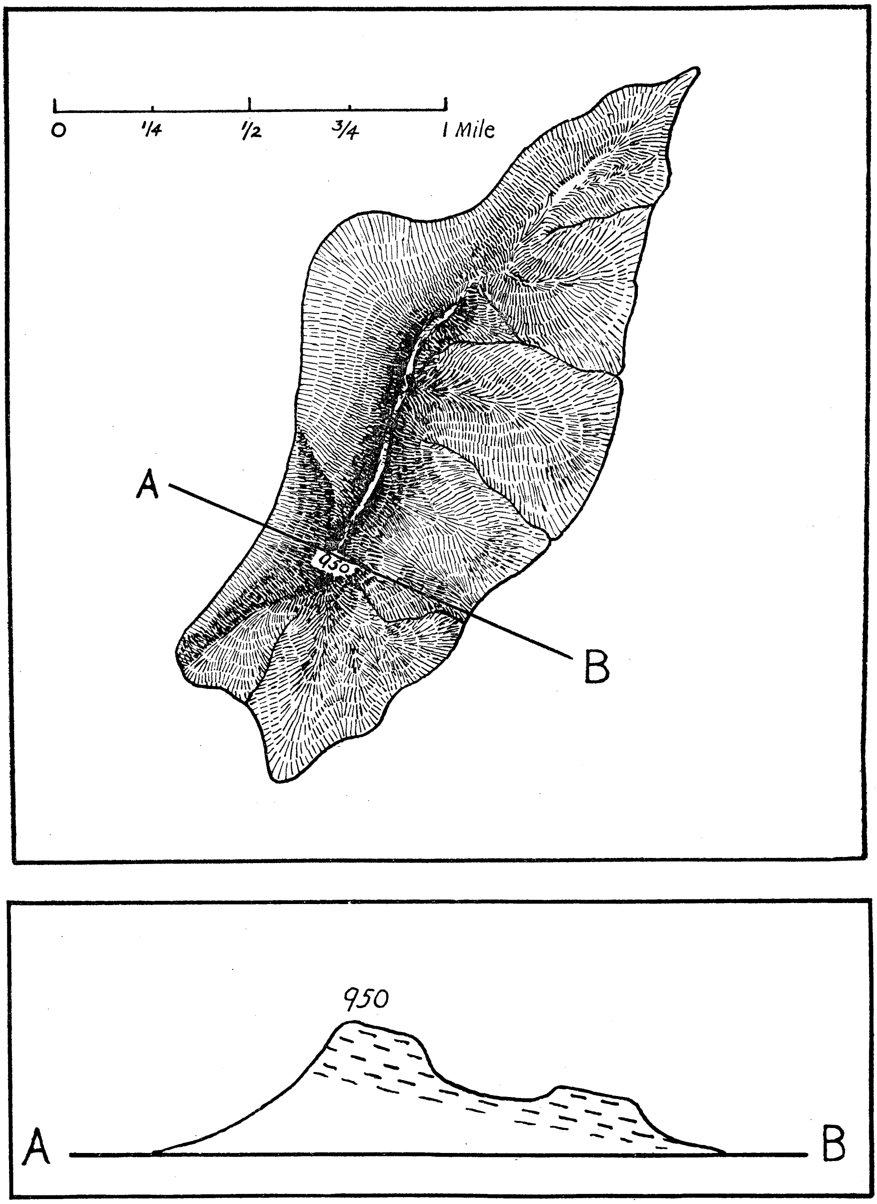


Figure 38. Hachure Map and Profile of Munia, Exploring Group.

and the erosion of the volcano to maturity require much time. It has been inferred that the planation of the elevated limestones of the Exploring group by wave-cutting may have occurred in the Glacial epoch. If Munia existed at that time, its slopes should have been cut by deep valleys and the valley-mouths should have been drowned at the close of the epoch. Since, however, the embayment of the coast of Munia is very slight, it is believed that the island was formed in late Glacial or early post-Glacial time; yet at a time sufficiently remote to permit of the mature erosion of the volcano. The elevated limestones underlying the débris from Munia are Pleistocene or Recent in date and hence confirm the evidence just given.

Kanathea.

The main portion of Kanathea is built on the remnants of an older, eroded volcano. Such remnants are still visible. No limestones appear; if they ever formed part of the island mass above sea, they have been lost by erosion.

The more recent part of Kanathea is built up of agglomerates and flows which have been carved into a sub-mature topography. The northwestern slopes of the island are little dissected and the slopes generally follow the initial dips of the volcanic beds. The eastern or windward side of the island has, however, deep, mature valleys.

The southern third of Kanathea is genetically distinct from its northern portion, and apparently represents a relic of the older volcano. Whereas the northern area is lateritized to a depth of but 2 or 3 feet, the southern has a late-mature topography of rounded hills, lateritized to depths of 15 to 20 feet.

Through northern Kanathea a central depression crosses the island from northeast to southwest. Entering this depression from the northeast, precipitous cliffs of agglomerate, 200 to 300 feet in height, are seen on either side. The dips of these beds are quaquaversal from a point somewhat east of the center of the valley. The lack of any streams competent to erode such cliffs and the quaquaversal structure of the agglomerates indicate that the central depression represents a crater. This crater has been breached.

A glance at the chart of Kanathea will show that the island has a long, narrow barrier reef extending to the northeast towards the Exploring group. The lagoon within the barrier reef is free of islands and has an average depth of 10 to 15 fathoms. The barrier reef ranges along the eastern and southern sides of the island; elsewhere the reef is fringing.

If an island existed here during the submergence of the andesitic hills of the Exploring group, it is reasonable to suppose that this island participated in that submergence. From the great amount of limestone which has been eroded from Vanua Mbalavu since the uplift of this formation, it is probable that the older volcano of Kanathea lost all its limestone veneer before the building of the more recent portion of the island.

The coastal outline of the newer portion of Kanathea, like that of Munia, is comparatively regular and shows little evidence of recent submergence. In fact, as at Munia, recent uplift is suggested by the incision of youthful valleys in the floors of the mature valleys of eastern Kanathea.

The history of the island of Kanathea is thus seen to be not unlike that of the Exploring group.

Mbengha.

The island of Mbengha is far removed from Kanathea, but many of its features are so similar that they will be discussed in the light of facts gathered at Kanathea. The reef about Mbengha is elliptical in shape, its longest axis extending northeast by southwest. The lagoon is 16 miles long and 10 miles wide. In its northwestern part lies Mbengha, a circular island four miles in diameter. The island is composed of agglomerates and flows of augite and hornblende andesite, carved into sub-mature topography.

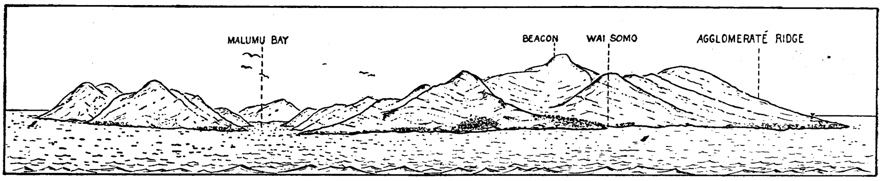


FIGURE 39. View of Mbengha as seen from the Northeast.

The northwestern slopes are long and even, following the original dip of the andesitic flows. The preservation of these slopes is probably due to the small rainfall on this side of the island.

The accompanying sketch of Mbengha (Figure 39), made from the northeast, shows the sharp peaks of its central portion and the deep bay of Malumu indenting its northeastern side. The bay represents the floor of an old crater. The high peaks at the western side of the bay are the edges of flows dipping away from the crater. Ash-beds which form the hills to the east of the bay also show quaquaversal dips.

Looking from the Beacon, the highest summit in Mbengha, towards the bay, several minor hills may be seen rising within the depression. As seen from the north, these hills appear to enclose the southern side of the bay, but actually the depression encircles the hills and a very slight subsidence would cut off the eastern side of the island and transform the hills into islands.

Other irregularities in the coast are believed to have an origin similar to that of Malumu Bay. They are irregularities, formed by the rapid erosion of weak ash-beds, and were not formed by the embayment of river valleys. The streams entering these bays are torrential, with boulder-covered beds within a hundred yards of their mouths. The evidences of embayment do not warrant the assumption that the island has subsided to any great extent; certainly not enough to support the view that the subsidence of Mbengha has converted a former fringing reef into the present barrier reef.

It has been shown, in the chapter on Viti Levu, that the larger island has experienced a number of earth movements, during which a lagoon floor was produced extending westward to the Yasawa islands. The Yasawa islands have been built up on this platform. It is thought probable that Mbengha also is a Post-Pleistocene volcano built on the ruins of an older one, which had been greatly eroded, then submerged and levelled by sedimentation and wave-cutting during a period when corals did not flourish.

The sub-mature topography of the island and the slight lateritization of its surface rocks show that the island is not very old. It appears to be of the same age as Munia and the more recent part of Kanathea.

The absence of signs of extensive submergence suggests that the younger Mbengha volcano, constituting the existing island, became active near the close of the Glacial epoch. Since that time the tropical climate has caused deep erosion, especially on the windward side.

Kandavu.

The group of islands of which Kandavu is the largest lies within the Great Astrolabe reef, some 40 miles south of Viti Levu. Kandavu is the southernmost of the group and extends for 15 to 18 miles in an east-west direction. A few miles off its northeastern shore is the circular island of Ono, some 4 miles in diameter. The other islands of the group are small ash and agglomerate remnants distributed over the northern part of the lagoon.

Kandavu is a long, rambling island separated into three nearly equal portions by constrictions. The isthmus connecting the central and western portions is so low that boats are dragged across by means of a tram-line.

Kandavu is built of andesitic flows and agglomerates of different ages. The eastern division of the island is sub-maturely eroded, but in the extreme west it includes a young volcano, Mbuke Levu, whose slopes are very slightly altered.

This topographic variety indicates a fairly complex history. No mention has hitherto been made of limestones in Kandavu, but the writer found a series of silicified rocks, charged with cavities, which have all the appearances of silicified limestones. These rocks outcrop at the head of a bay in the middle of the southern coast of the eastern segment of the island. Back of the little village of Kandavu, they form a series of cliffs, 100 feet in height, over which a stream cascades. The stream drains sub-mature hills of andesite in the interior. The silica introduced into the altered limestone was probably derived from the andesite which overlies the limestone. The limestones rest on an irregular surface of brecciated volcanic rocks, resembling rhyolitic tuffs but may possibly be a silicified andesitic ash. The accompanying cross-section, (Figure 40), shows the relations of the rock types. The limestones may have been formed in one of the periods of crustal quiescence which have interrupted volcanic activity in the island.

The coast of Kandavu gives immediate evidence of subsidence. It is the best example of an embayed shore-line known in Fiji. This is specially true in the south, where every little river emptying into the head or side of a bay shows a delta flat and flood plain. The same relations hold in Ono.

The John Wesley Bluffs at the northeastern side (northern coast) of the western segment of the island represent one of the striking features. The bluffs are nearly vertical and rise to a height of 150 to 200 feet. Since there is no barrier reef off the coast, it may be reasoned that the bluffs were formed by wave-cutting. However, the highest cliffs are those which do not receive the full force of the waves but rather are situated along a sheltered bay-side. If wave-action had cut back the coast at this point, there should be a sea-cut bench in front of the cliffs; yet near the cliffs the depths reach 107 fathoms, and, at their very base, the lagoon depths are 12 to 16 fathoms. Even if the cliffs were cut by the waves during the Glacial epoch, the waves, working at present sea-level since that period, should have cut a bench of considerable width. Such a bench does not exist.

The cliffs may, therefore, be due to a sub-recent wave-cutting, followed by recent subsidence; or they may be due to faulting. Hence the embayment of the local coast-line was not caused by the return of water to the ocean after the Glacial epoch but to actual subsidence. Such subsidence may be the more readily postulated in view of the general crustal instability in Fiji.

The presence of nearly a hundred feet of limestone at the eastern side of the island, overlying an irregular surface of volcanic rocks, leads to the inference that Kandavu was probably involved in the general subsidence affecting most of the islands of Fiji. The dismembered slopes of agglomerate and ash composing the numerous islands at the northern end of the Kandavu lagoon show that profound erosion has taken place within the island group. It may be that an older island once lay at the eastern end of the present lagoon of Kandavu, separated by a strait from another volcanic mass which now forms the small island of Solo within a separate lagoon. The deep erosion and subsidence of these volcanic islands allowed the present reefs to develop about them. Later extrusion then built up the western part of Kandavu.

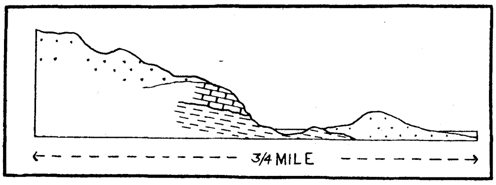


FIGURE 40. Cross-section of Elevated Limestones near the Village of Kandavu, Kandavu.

Blocked — elevated limestone. Dashed — silicified ash. Dotted — andesite.

In contrast to this view, it may be held that after the formation of the island in its present outline, a recent subsidence has tilted down its eastern portion and so formed the Great Astrolabe Reef. Lack of sufficient data makes impossible a connected outline of the development of Kandavu, but, in general, it has had a history not unlike that of the Exploring Group.

GENERAL REVIEW OF THE GEOLOGICAL HISTORY OF FIJI.

The various events in the geological history of Fiji, having been set down in tabular form in their appropriate places, need not be fully re-stated. A comparison of the tables will give the best general review of the history of the islands. There have been four periods of volcanism: a rhyolitic period, either contemporaneous with, or followed almost immediately by, an andesitic period; after a long interval, another andesitic period; and a recent period of basaltic eruptivity.

The relations of erosion, volcanism, and earth movements may be expressed briefly as follows: —

Batholithic intrusion, erosion, volcanism, brief erosion, subsidence, uplift, erosion, volcanism, subsidence, uplift, erosion, volcanism, submergence.

Little is known concerning the geological dates of these events. The fauna of the South Sea Islands has not been sufficiently correlated to fix the age, or ages, of the elevated limestones. Dall (1898, p. 168) states concerning the fossil mollusks, collected by Alexander Agassiz from the coastal-plain series, "None of the genera are extinct. The rock, however, looks decidedly too old for Pleistocene. I should say the fossils were younger than Eocene and might be either Miocene or Pliocene."

Skeats found in the upraised limestones of Mango a species of foraminifera, Orbitoides sumatrensis, which is similar to a Miocene form described by C. W. Andrews from Christmas Island, Indian Ocean, (Skeats, 1903, p. 120.)

Woolnough (1903, p. 464) states that the elevated reef near Suva "has yielded a considerable number of fossils of various kinds, the assemblage of which appears to indicate that the bed is not newer than Pliocene. Conspicuous among these fossils is a tooth of a large Carcharodon."

In contradiction to this, Brady (1888, pp. 1–10) finds that the marls associated with the coralliferous limestones of Suva are, without the "slightest hesitation," post-Tertiary. He states, "of the ninety-two species of Foraminifera which have been identified, eighty-seven are forms still living in the neighborhood of the Pacific Islands."

Dr. T. W. Vaughan of the United States Geological Survey kindly examined the corals collected by the writer from the Lau Group and from the elevated reef at Suva. He pronounced them Pleistocene or Recent, (See Table I).

TABLE I.

List of Fossils Collected, with Heights above Sea.

A. *Corals,*— Determined by Dr. T. W. Vaughan.
(Many of the species are figured in Pub. 213, Carnegie Institution of Washington.)

Acropora sp.?, South of Ndelai Yaloi, Kambara, (8 to 10 feet).
Dendrophyllia sp.?, Hill just east of the mouth of the Singatoka river, (60 to 70 feet).
Diploastrea heliopora (Lamarck), 3½ miles east of Na Sana Sana, S. W. Viti Levu, (15 to 20 feet).
Diploastrea heliopora (Lamarck), West of Nandi bay, S. E. Vanua Levu, (10 to 15 feet).
Favia stelligera (Dana), South of Ndelai Yaloi, Kambara, (8 to 10 feet).
Favia aff. F. speciosa (Dana), Navindamu, Fulanga, (10 feet).
Favia sp.?, Mana Islands, Ono-i-lau, (10 to 15 feet).
Favites abdita (Ellis and Solander)?, Nasangalau, Lakemba, (75 to 100 feet).
Favites abdita (Ellis and Solander)?, West of Nandi bay, S. E. Vanua Levu, (10 to 15 feet).
Fungia sp.?, Walu bay, Suva, Viti Levu, (30 to 50 feet).
Fungia sp.?, Mbuambua, West of the mouth of the Singatoka river, (15 to 20 feet).
Galaxea clavus (Dana)?, Navindamu, Fulanga, (75 to 100 feet).
Galaxea sp.?, Nasangalau, Lakemba, (75 to 100 feet).
Goniastrea sp.?, Ndelai Yaloi, Kambara, (8 to 10 feet).
Goniopora sp.?, Navindamu, Fulanga, (10 feet).
Hydnophora cf. H. exesa (Pallas)?, Dalithoni, Vanua Mbalavu, (10 to 15 feet).
Leptastrea bottae (M. Edw. & H.), Dalithoni, Vanua Mbalavu, (10 to 15 feet).
Leptoria tenuis (Dana)?, Yanuia Islands, Ono-i-lau, (10 feet).
Leptoria gracilis (Dana), West of Nandi bay, S. E. Vanua Levu, (10 feet).
Maeandra aff. M. lamellina (Ehrenberg), Yanuia islands, Ono-i-lau, (10 to 15 feet).
Maeandra (Coeloria) sp.?, Mbuambua, west of the mouth of the Singatoka River, (15 to 20 feet).
Maeandra sp.?, Nasangalau, Lakemba, (75 to 100 feet).
Montipora sp.?, Dalithoni, Vanua Mbalavu, (10 to 15 feet).
Orbicella sp.?, South of Ndelai Yaloi, Kambara, (8 to 10 feet).
Pocillopora grandis (Dana)?, Nasangalau, Lakemba, (75 to 100 feet).
Porites sp.?, South of Ndelai Yaloi, Kambara, (10 to 15 feet).
Porites sp.?, Mana islands, Ono-i-lau, (10 to 15 feet).
Symphyllia nobilis (Dana)?, South of Ndelai Yaloi, Kambara, (10 to 15 feet).
Stylophora pistillata (Esper)?, Nasangalau, Lakemba, (10 to 15 feet).
Stylophora sp.?, South of Ndelai Yaloi, Kambara, (10 to 15 feet).

B. *Mollusca,*— Determined by Dr. Paul Bartsch.

Cardium sp.?, Walu bay, Suva, Viti Levu, (30 to 50 feet).
Cypraea sp.? Walu bay, Suva, Viti Levu, (24 feet).
Lithophagus sp.?, Walu bay, Suva, Viti Levu, (25 feet).
Lithophagus sp.?, Na Sana Sana, S. W. Viti Levu, (10 to 15 feet).
Lucina sp.?, Mbuambua, West of the mouth of the Singatoka river, (10 to 15 feet).
Pecten sp.?, Na Sana Sana, S. W. Viti Levu, (10 to 15 feet).
Pecten sp.?, Mbuambua, Singatoka district, (10 to 15 feet).
Tapes sp.?, Na Sana Sana, S. W. Viti Levu, (10 to 15 feet).
Trochus sp.?, Na Sana Sana, S. W. Viti Levu, (10 to 15 feet).
Trochus sp.?, Mbuambua, S. W. Viti Levu, (10 to 15 feet).
Trochus sp.?, Walu bay, Suva, Viti Levu, (25 feet).
Turritella sp.?, Na Sana Sana, S. W. Viti Levu, (10 to 15 feet).
Venus sp.?, Na Sana Sana, S. W. Viti Levu, (10 to 15 feet).
Venus sp.?, Mbuambua, S. W. Viti Levu, (10 to 15 feet).
Venus sp.?, Walu bay, Suva, Viti Levu, (25 feet).

C. *Pisces.*

Diodon sp.?, Walu bay, Suva, Viti Levu, (25 feet).
(A new species now being studied by Dr. C. R. Eastman.)

The rocks of the coastal-plain series, of which the Suva limestone forms a part, appear to be decidedly younger than the limestones of the interior. Evidence in favor of this view is as follows:—

(1). Boulders of the older limestones occur in the basal conglomerate of the coastal series near Na Roro, 5 miles from the mouth of the Singatoka River.

(2). The interior marls are highly folded, in contrast to the low-dipping coastal series.

(3). The coastal series are much less recrystallized than the interior marls.

Woolnough (1907) has indicated on his maps of Vitu Levu only one series of marls and has placed this series in the Middle Tertiary. The writer early came to the conclusion that there were two series of rocks. Later he found that the order of events in Vitu Levu closely correspond to the order as made out by Mawson (1905, pp. 471–472) in the adjacent islands of the New Hebrides. These events may be tabulated as follows:

(1). "— local shallow marine conditions and subdued volcanic activity.

(2). "— development during Miocene times of a fold-ridge." "The folding force would appear to have been exerted from the direction of Fiji, against the foreland of New Zealand crystalline schists and gneisses.

(3). "— subsidence of outer wing (of fold) followed by extensive late Miocene andesitic eruption along the plane of weakness."

(4). "— faulting of the inner wing of the fold along the line of the present active volcanoes, letting down the sea floor to the east, thus putting fairly deep water between the New Hebrides and the Fiji land-surface.

(5). "— During all this period of volcanic activity, extensive submarine tuffaceous beds were accumulating above the folded Miocene series; the earlier deposits followed later by varieties of soapstone. No interbedded coral limestone was met among these tuffs." "Capping this series, are the raised coral reefs elevated to heights of over 2000 feet. The oldest of these is referable to a period not earlier than late Pliocene and probably not much later as it has since been intruded by lava from centers now extinct."

(6). "— The elevatory movements evidenced in these raised reefs is of a see-saw type, greatest in the west and least (probably in many cases a minus quantity) in the east, where

(7). "— the great recent basic eruptions have taken place."

Mawson regards "the elevatory tendency" as a "continuance of the tectonic movements so critically developed in Miocene times," but considers certain of the uplifts as the direct outcome of volcanic intrusion.

It is believed, therefore, that the older folded series of central Viti Levu are the equivalents of Mawson's Miocene folded series of the New Hebrides. The formation of the coastal-plain series of Viti Levu would then be referred to late Pliocene or Pleistocene time. The elevated limestones of the Lau and Yasawa Groups are correlated, from fossil evidence, with the coastal-plain series. The submarine tuff beds of the New Hebrides, as described by Mawson, are very similar to the rocks of central Vanua Levu. The lack of folding in central Vanua Levu probably means that these tuffs are essentially of the same age as the elevated limestones of the Lau Group and late Pleistocene instead of contemporaneous with the Miocene folded beds of Viti Levu.

As Mawson has stated for the New Hebrides, the elevatory movements of the coastal series in Fiji have been of a see-saw type and have continued to very recent times. The series is believed to be essentially conformable throughout, though the uplift of the islands of the Lau Group has continued through a period from late-Pliocene to Recent. Thus the coastal limestones near the mouth of the Singatoka River may be more recent in date of uplift than the Rewa marls, but they belong essentially to the same series.

The ages of the plutonic rocks of central Viti Levu and of the sediments which they intrude can only be conjectured. The erosion which exposed these rocks was completed before the Miocene depression. They are doubtless at least as old as the early Tertiary.

BEARING OF THE RESULTS OF THE EXPEDITION ON THE CORAL REEF PROBLEM.

The several theories to account for barrier reefs and atolls are summarized, following Davis (1914) in part, by the outline given below.

I. Theories which do not involve a positive shift of the sea-level.
  A. Atolls built on submerged craters.
  B. Atolls formed by upward growth on still-standing banks.
    1. The banks are graded to the proper level for coral growth by the waste from plankton. (Murray, 1880)
    2. The banks are formed by rapid wave action leveling the scoriatous waste of submarine volcanoes. (Wharton, 1897)
  C. Barrier reefs and atolls formed by progressive outward growth of a fringing reef and the solution of an inner lagoon by ocean water. (Murray, 1880)
  D. Veneering reefs on sea-cut platforms.
    1. Platforms are cut about high, volcanic islands which are later reduced to sea-level by subaerial erosion. (Tyerman and Bennet, 1832)
    2. Platforms are cut about elevated masses of coralliferous limestone. (A. Agassiz, 1899)

II. Theories involving a positive shift of the ocean level.
  A. Atolls and barrier reefs built on subsiding islands. (Darwin, 1842)
  B. Atolls and barrier reefs built on platforms cut by Pleistocene wave-action and later submerged by the return of Glacial waters to the ocean. (Daly, 1915)

Murray's theory involving solution by ocean water has been discarded by most geologists, because of its quantitative inadequacy. Many writers believe that the banks are antecedent to the veneering reefs since they have greater extent than the reefs (Vaughan, 1914, p. 32), but do not attempt to explain the origin of the bank. In the next few pages the facts gathered in Fiji will be discussed in the light of the above theories.

While the earliest facts known concerning the two large islands of Viti Levu and Vanua Levu show that they were continental land masses, they were later submerged and covered by volcanic débris. Vanua Levu is composed in large part of submarine volcanic rocks.

The later history of the island has been characterized by uplift during Pleistocene and Recent times. Indeed, the Fiji group as a whole cannot be included in Darwin's or Dana's typical areas of progressive subsidence. The upward movement in southeastern Vanua Levu has continued into so recent times that near Vunelangi a lagoon flat and outer reef are preserved in all their details though elevated 50 to 75 feet above the present sea-level.

No remnants of coralliferous limestone occur near the summit or along the upper flanks of the ridges of Vanua Levu. This may best be explained by the very rapid erosion of the underlying weak deposits of volcanic dust, ash, and submarine tuff. The delta flats formed from this débris which should surround the island are lacking for the most part, though near Vunelangi remnants of a bench of such volcanic waste are found. It is apparent that after uplift the fine clays are soon shifted to the new level. Yet even then they should form delta flats near the present sea-level as they do near Vunelangi. That similar extensive flats do not exist is proof that the recent uplift in southeastern Vanua Levu is replaced throughout the other and greater part of the island by contemporaneous subsidence.

Previous conditions in Vanua Levu have been obscured by erosion and subsidence. Where uplifted reefs occur they have been elevated only one or two hundred feet. They rest on old land surfaces, indicating subsidence. The recent positive shift of the ocean level cannot be identified with the rise of the waters at the close of the Glacial period. It is much too recent.

From the earlier discussion of Viti Levu and from what has been said of Vanua Levu it is apparent that the larger islands of Fiji have had a very complicated history, and that it is futile to attempt to find any one theory which explains the present position of their reefs.

Conditions in the Lau islands are not so involved. Their elevated limestones are spoken of by Alexander Agassiz (1898) as Tertiary but the writer considers them Pleistocene or Recent. Two distinct problems are presented. The older elevated limestones represent one cycle of events; the modern reefs represent another.

With regard to the first cycle, Agassiz (1899) has stated, "Granting even, as is very probable, that when these Tertiary limestones were formed they were formed in great part by subsidence, and in part by accretion from the carcasses of the invertebrates living upon their surface, this would in no way help us to a satisfactory explanation of the formation of atolls and of barrier reefs by the growth of the corals of the present epoch." "The only evidence we have of the great thickness of coral reefs, such as is required by the Darwinian theory of the formation of atolls and of barrier reefs, is based upon the great thickness of the so-called elevated reefs observed in the Pacific by Dana, Darwin, and others.....That the latter are true coral reefs is more than doubtful. Those rocks are probably great masses of limestone similar to the so-called elevated reefs of the West Indies and the Pacific."

The mere fact of the deposition of limestone on a subsiding basement does not, in accordance with this statement, establish the truth of Darwin's theory. The elevated masses must be proven to be of coral origin, to have the reef form, and to rest unconformably on a volcanic substructure.

Several observers have considered the raised rims of such islands as proof of their atoll origin. The writer agrees with Agassiz that such evidence is not always conclusive, since atmospheric solution may lower the surface at the center of an elevated limestone bank faster than the surface at its edge, as instanced by the Florida plateau. Yet, even if this fact is established, one may well question that differential solution is competent to explain the great relative heights of the rims in Kambara and Wangava, which respectively average 260 and 300 feet higher than the central depression. If these depressions are due entirely to solution, it would appear that the underground channels, which conduct the drainage of the islands to the sea, ought long ago to have breached the surrounding rims.

Again, if these islands are truly raised atolls it may be held that reef limestones should characterize their rims while coral débris and other fine-grained material should dominate in the lagoon deposits. With this point in mind a study was made of the outer edges of the islands. Coral heads were often found in place, but in no greater abundance than within the lagoon deposits. Moreover, they were of the rounded type and not the fungus-shaped forms that occur at the edges of the present, growing reefs. The writer could not find a locality which might definitely be called the edge of an old atoll.

However, the atoll hypothesis need not be abandoned. The study of a growing reef shows that the characteristic forms of a reef-edge are lost a few feet behind that edge. The ocean waters, pressing through the over-hanging, porous edge, are continually destroying the coral heads and throwing their fragments on to the reef-flat. Often blocks of limestone, weighing several tons, are torn from the edge and cast on to the flat. It appears that the growing reef is only a thin veneer covering a mass of débris. If this conception is true, all evidence of a former barrier reef or atoll would soon be destroyed after uplift, and it is unnecessary to assume a considerable benching of the atoll in order to expose the inner lagoon limestones. The writer believes there is more chance for the preservation of the rounded coral heads growing near the centers of lagoons, where wave-work is less vigorous, than for the preservation of the reef coral at the edge of an atoll.

In spite of the lack of conclusive evidence the writer is inclined to believe that such islands as Kambara and Fulanga are elevated atolls. Further grounds for this belief are as follows: —

1) It is impossible to believe that the coralliferous limestones merely veneer older, non-coralliferous limestones, since the latter are nowhere exposed in spite of profound erosion.

2) The fossil corals occurring in the elevated limestones are identical with living species which are now constructing atoll-reefs.

3) The atoll form of the islands is too strongly marked to be merely the result of differential solution.

4) The normal limestone-coral banks of the present day are higher at their center than at their edges and hence, if they were elevated, would not have interior depressions.

Ancient atolls are therefore preserved in the uplifted limestone islands of Fiji; likewise an ancient barrier reef is recognized in the elevated reef of Lakemba. Most important of all is the fact that in all known cases the older limestones rest unconformably on an eroded basement.

Daly, however, (1915, pp. 199–200) infers that certain islands of Fiji which have the atoll-form were developed on Pleistocene wave-cut benches in post-Pleistocene time, and were subsequently elevated. Kambara and Fulanga belong in this class. Such a conception would divide the cycle of the older limestones into two parts and would negative the view that the elevated atolls developed as a result of the subsidence of their eroded basement. In the older division would be placed the limestones planed by Pleistocene wave-cutting; in the younger division the post-Pleistocene atoll-limestones would be found. Accepting this hypothesis, an unconformity should exist between the two limestone series. If such an atoll were elevated over 40 fathoms, the depth of a stable, Pleistocene, wave-cut bench below the present sea-level according to Daly, the unconformity should be exposed, if the outer reef-face were sufficiently eroded. The atoll of Fulanga has been elevated more than 45 fathoms, that of Kambara more than 60 fathoms; yet no evidence of an unconformity was seen in the retreating sea-cliffs of these islands.

Again, if Fulanga were elevated 45 fathoms, the Pleistocene bench, according to the hypothesis, should appear near sea-level and the present lagoon depth of 10 fathoms be explained most logically by recent subsidence. The depth of the Fulanga lagoon corresponds closely to the depths within adjacent modern reefs. Neither Fulanga nor Kambara have any indications of benches, either above or below sea-level, which may be interpreted as Pleistocene, wave-cut platforms.

If the Glacial-control theory is still adhered to, the atolls must be pre-Pleistocene in age, but Daly considers that atolls and barrier reefs originated specially in post-Pleistocene time and were perhaps rare forms in the pre-Glacial oceans. If these atolls were pre-Glacial, they would easily have been destroyed by Pleistocene wave-cutting.

There is no evidence that the cycle of the elevated limestones was broken by a period of Pleistocene wave-cutting. The writer believes therefore that, in the older cycle, barrier reefs and atolls originated by the subsidence of eroded, volcanic surfaces.

The present cycle was initiated by the uplift of the older limestones. During the cycle these limestones have been differentially elevated and their present state of erosion indicates that they were by no means elevated contemporaneously. Vatu Vara is 1030 feet high and remarkably well preserved. Vekai is but 12 feet high and represents the final residual mass of a former island destroyed by atmospheric solution. A close study of the charts leads to the conclusion that the less the erosion of an island, the less is the depth of its surrounding lagoon. This inference holds true in spite of the fact that by progressive erosion the lagoons should be filled and is explained by a recent subsidence.

All of the islands are being rapidly reduced to sea-level by atmospheric solution. Sea-level flats dotted by residual masses of limestone should be the ultimate stage of this process. Portions of Fulanga and Ongea present examples of this stage, but such examples are rare. Lagoons dotted by undercut islets, the submerged complements of such flats, are, however, very common. All the recently uplifted islands have no lagoons, or else shallow lagoons. All the eroded islands have lagoons indicating subsidence. Hence still-stand with the production of large solution flats near sea-level is very uncommon. The inference follows that uplift is soon followed by subsidence. In this way a new generation of atolls is developed on the eroded and submerged platforms of the older limestone masses.

Table II presents the facts concerning the size and maximum depth

TABLE II.

Dimensions of Reefs and Deepest Lagoon Soundings in the Lau Group.

(The elevations of limestone masses within the reefs are given immediately after names.)

	Width miles	*Length* miles	*Depth* fathoms		*Width* miles	*Length* miles	*Depth* fathoms
Wailangilala	2.7	4.	23	Reid Reef (60′)	6.	8.	21
Duff Reef	2.	6.67	11	North Argo Reef (80′)	5.3	10.6	26
Williamson Reef	1.	1.3	13	South Argo Reef	10.	24.	36
Dibble Reef	1.3	2.25	15	Lakemba (320′)	6.	13.3	14
Naitamba (610′)	3.3	4.	9	Aiwa (210′)	3.3	9.3	23
Kimbombo	2.6	5.3	11	Oneata (160′)	6.	11.3	20
Bell Reef	1.6	2.3	12	Olarua	1.6	2.3	7
Malima	2.3	2.3	11	Thakau Vuite	2.	3.3	16
Exploring Group	21.3	26.6	94	Komo	3.3	5.3	17
Kanathea (350′)	5.3	9.3	15	Mothe	3.5	10.6	8
Mango (630′)	4.	4.	2	Thakau Motu	3.	6.	24
Malevuvu Reef	2.	2.6	14	Namukai Lau	3.	6.7	13
Vekai	1.8	2.	17	Yangasa Group (390′)	6.	10.	17
Katafanga (180′)	2.6	4.	13	Thakau Levu	2.	5.	13
Tuvuthá (800′)	3.	4.3	9	Fulanga (260′)	4.6	6.	10
Thakau Tambu	2.6	3.3	11	Ongea (270′)	5.2	8.	13
Thakau Lasemarawa	2.	2.3	6	Ono Group (15′)	4.	6.7	6

of the barrier reefs and atolls of the Lau islands. Fifty per cent of the lagoons have maximum depths of between 60 and 90 feet. Wave-erosion is ineffective at such depths within a lagoon. Solution by ocean water is as inefficient a cause. Submergence is the only alternative, and, since the rise of the waters is more recent than the return of the waters after the Glacial period, an actual subsidence must have occurred.

It is apparent that the movements have been very irregular. They are confined to small segments of the earth's crust and are undoubtedly associated with volcanic activity. In part the movements have been due to the transfer of material from the inner to the outer portions of the earth's crust; and in part to the secular condensation of the extruded lavas and pyroclastics. (Cp. Gerland, 1895, p. 56, and Daly, 1915, p. 232).

Referring again to the theories of coral growth (p. 88), it is seen that none of them, taken by itself, is applicable to the Lau islands. None of the modern reefs appears to be growing on a submerged crater rim. In each observed case, a foraminiferal deposit occurring beneath elevated limestone rests on an eroded basement and gives no evidence of having assisted in aggrading a submerged, volcanic mass to the level of coral growth. Indeed, in only one instance, near Savu Savu bay, Vanua Levu, was an uplifted reef found which rested on a contemporaneous, submarine lava flow, and none was found resting on benches which appeared to have been cut by submarine erosion.

Only Darwin's theory postulates a subsiding basement eroded above sea-level. But this theory is firmly based on the conception of progressive, though intermittent, subsidence of large segments of the earth's crust. The elevated limestones of Fiji were deposited during pre-Recent subsidence. Since the Pleistocene period, the algebraic sum of the earth movements has been positive and uplift has resulted; although the sum, if reckoned from the early Tertiary, is negative and the ultimate result has been subsidence. However, the present reefs are dependent for their form upon Pleistocene and Recent movements. Hence it cannot be said that the modern reefs of Fiji fully support Darwin's theory, since their history is not expressed by the simple succession of fringing reef, barrier reef and atoll. The history of the older, elevated limestones more nearly coincides with Darwin's theory than does the history of the modern reefs.

SUMMARY OF THEORETICAL RESULTS.

The writer's views concerning the origin of barrier reefs and atolls may be summarized as follows:—

1. The present coral reefs have been developed on surfaces which have been formed, as Agassiz in principle held, by the integration of a number of processes acting during several geological periods. These processes are, (a) atmospheric erosion, (b) wave-cutting, (c) sedimentation, and (d) volcanic aggradation.

2. There is no logical reason why a coral atoll, given the proper submarine bench, should not have existed in pre-Glacial as well as in post-Glacial time.

3. It is demonstrated that the older coralliferous limestones of Fiji developed on a subsiding basement of eroded volcanic rocks and formed barrier reefs and atolls. Very few of the modern reefs have been formed in a similar way.

4. Certain atolls are now developing on basements of elevated

limestone which have been eroded to fairly even surfaces by atmospheric solution, and later submerged.

5. Areas of subsidence in Fiji have undoubtedly been compensated by areas of uplift. In the latter areas shoals or islands have been formed, on or about which coral reefs have developed.

6. In Fiji, the Darwinian order of fringing reef — barrier reef — atoll is not generally the result of progressive subsidence. On the other hand, the association of the three reef forms is due to a series of irregular movements during which platforms are developed by the integration of the above-mentioned processes.

7. The detailed history of the islands of Fiji shows that they have not been stable during recent geological time, and an adaptation of Darwin's theory may apply to many of these islands. Yet it is not safe to assume its universal application.

In conclusion, it may be stated that in Fiji as elsewhere (Cp. Vaughan, 1914, p. 31) the modern reefs are developing on basements which are antecedent to the reefs. Most of the older writers postulated that the reefs rested on wave-cut benches, without telling how such benches could be carved in spite of the protection of the reefs, or why the reefs should be absent. The Glacial-control theory solved the problem by assuming that the reefs were removed during the Glacial period. The data assembled by Daly (1915) and Vaughan (1916) convince the writer that Pleistocene benches exist very generally throughout the coral seas. Nevertheless, the platforms in Fiji are much more modern in their development. The writer was unable to discover in these islands any evidence of Pleistocene wave-cut platforms.

PART II.—PETROGRAPHY OF FIJI.

By Wilbur G. Foye.

TABLE OF CONTENTS.

Page

- Introduction 99
- Previous work 99
- Sedimentary rocks 101
  - Marl 101
  - Conglomerate 102
  - Limestones and marbles 104
- Igneous rocks 105
  - Rocks from Viti Levu 105
    - Tonalite 105
    - Dioritic gabbro 107
    - Aporhyolite 107
    - Feldspar porphyrite 108
    - Olivine basalt from Tamavua River 108
    - Olivine basalt from Lautoka 109
    - Olivine basalt from Na Sana Sana 109
  - Rocks from Mbengha 110
    - Basalts composed chiefly of Augite and Feldspar 110
    - Basalts composed chiefly of Augite and Feldspar with Olivine 111
    - Basalts composed chiefly of Augite and Feldspar with Hornblende 111
  - Rocks from the Yasawa Group 111
    - Basalt 111
    - Hornblende andesite 112
  - Rocks from Vanua Levu 113
    - Summary of the petrography of Vanua Levu as given by Guppy 113
      - Plutonic rocks 113
      - Volcanic rocks 113
    - Description of rock types collected by the writer 115
      - Rocks from the Mbutha Bay district 115
        - Basalt 115
        - Hypersthene basalt 115
      - Rocks from the Lambasa district 115
        - Gabbro 115
        - Basalt 117
        - Foraminiferal basaltic ash 117
        - Andesitic porphyrite and pitchstone 117
      - Rocks from the Savu Savu Bay district 118
        - Hypersthene basalt 118
        - Basalt 118
      - Rocks from the divide between Lambasa and Savu Savu Bay districts 119
        - Basaltic conglomerate 119
        - Gabbro porphyrite 119
  - Rocks from Taviuni 120
    - Andesitic basalt 120
    - Olivine-gabbro porphyrite 120

PAGE.
Rocks from the Lau Islands 121
  Vanua Mbalavu 121
    Andesite from the southwestern side 121
    Andesite from the western side 122
    Basalt from Koro Mbasanga 122
    Vesicular Basalt from Mua Mua 122
    Basalt from the north side 122
    Andesitic basalt from Tota 123
  Yanu Yanu 124
    Andesite 124
    Olivine basalt 124
  Susui 125
    Andesite 125
    Basalt 125
  Munia 125
    Olivine basalt 125
  Thikombia-i-lau 126
    Andesitic basalt 126
    Vesicular basalt 127
  Kanathea 127
    Olivine basalt 127
  Tuvuthá 128
    Basalt 128
    Olivine basalt 128
  Lakemba 128
    Andesite 128
    Olivine basalt 129
  Ono Group 129
    Vesicular andesite 129
    Olivine andesite from Ndoi 129
    Basalt 129
    Olivine andesite from Ono Levu 130
  Kambara 131
    Olivine basalt 131
  Moala 132
    Olivine basalt 132
Rocks from Kandavu 132
  Trachytoid andesite 132
  Hornblende andesite 133
  Hornblende-biotite andesite 134
  Olivine andesite 134
  Olivine basalt 135
Solo Rock 135
  Andesitic tuff 135
Petrology of the Fiji Islands 135
  Association of plutonic rocks 135
  Volcanic succession in Viti Levu 136
  Comparison of the lavas of Ovalau, Mbengha, and the Yasawa Group with those of Viti Levu 137
  Volcanic succession in Vanua Levu 137
  Volcanic succession in the Lau Group 138
  Volcanic succession in the Kandavu Group 139
  General Summary of the volcanic succession in Fiji 139
  Differentiation in the lavas of Fiji 140
Table of analyses 142
Bibliography 143

INTRODUCTION

The main object of the expedition to Fiji was the study of the geology of coral reefs. It was not possible therefore, in the allotted time, to collect a series of igneous rocks representative of the nature and distribution of the various types in the islands. Specimens were collected, for the most part, from localities near the seashore where they were associated with coral limestones.

It will be evident in the discussion of the petrology of the islands, that the solution of many important problems must await further investigation.

PREVIOUS WORK.

Many travellers have collected rocks in Fiji from time to time, but as few of these men were petrographers little has been written on the petrology of the islands. One of the most important contributions has been made by E. W. Skeats (1903). He added materially to the knowledge of dolomitization throughout the group, by publishing a long list of analyses of elevated limestones.

Dana, Kleinschmidt, Gräffe, Macdonald, Seeman, Horne, and Agassiz, all brought back extensive collections of rocks, but these rocks were described by other investigators. Woolnough, Andrews, Guppy, and Cochrane, alone have described their own specimens.

The first detailed petrographic work on rocks from Fiji was done by Arthur Wichmann, (1882). Wichmann described a series of rocks collected by Th. Kleinschmidt (1879) during an expedition to the islands in 1876–78. He also included in his paper, the description of a smaller collection, made by Gräffe (1869) in the years 1862 and 1865. The rock types determined were as follows: —

granite,
quartz porphyry,
syenite porphyry,
foyaite,
diorite,
diabase,
gabbro,
andesite,
basalt,
tuff,
amphibolite,
eurite,
quartzite.

Members of the Challenger Expedition, while anchored at the port of Kandavu, collected a few rocks. These were described by

A. Renard (1888) in the report of the Expedition. Only three types were noted: —

hornblende andesite,
augite andesite,
biotite andesite.

In 1899, Arthur S. Eakle (1899) described some of the igneous rocks, collected by Alexander Agassiz during his voyage among the islands. The types determined were: —

diorite-granite,
augite andesite,
augite-biotite andesite,
augite-olivine andesite,
hypersthene andesite,
hornblende andesite,
basalt,
olivine basalt.

E. C. Andrews (1900) visited the islands in 1898 and in a report on the "Limestones of the Fiji Islands" gave a brief description of the volcanic rocks which he collected.

In 1901, Walter G. Woolnough (1903) made a journey across Viti Levu, and, for the first time, found granites in place. He described the following rock types: —

granite,
quartz diorite,
diorite,
augite andesite,
pyroxene andesite,
hornblende andesite,
olivine andesite,
porphyritic basalt.

H. B. Guppy (1903), during his travels in Vanua Levu between 1896 and 1899, collected a large number of rocks which he carefully described in his book concerning the geology of this island.

N. D. Cochrane (1911), acting as Government Mining Adviser, described briefly a large number of rocks from the islands. The chief types noted were: —

I. Sedimentary Rocks.
  redistributed tuff,
  tuffaceous marl,
  limestone,
  marble.

II. Volcanic Rocks.
  tuff,
  basalt,
  dolerite,
  augite andesite,
  hornblende andesite,
  mica andesite,
  olivine andesite,
  hypersthene andesite,
  trachyte,
  porphyrite,
  gabbro,
  diabase,
  diorite,
  quartz diorite,
  hornblende granite,
  biotite granite.

SEDIMENTARY ROCKS.

The main types of sedimentary rocks collected during the present expedition were as follows: —

marl,
conglomerate,
limestone,
marble.

Red sandstones and shales were found in the beds of streams draining the central part of Viti Levu. Their source was not located. Other sandstones, composed of slightly river-worn volcanic materials, were commonly found interbedded with the boulder conglomerates which lie on the slopes of maturely-eroded andesites or form the basal layers of the coastal sediments of Viti Levu.

Marl. Two types of marl may be found in Fiji. The first type belongs to the folded series of central Viti Levu; the second, forms a part of the coastal-plains series.

The marl of central Viti Levu is brownish drab in color and has the usual even, fine-grained texture of these rocks. Rocks of this description occur to elevations of 2000 to 2500 feet and are often highly folded.

Under the microscope, the rock shows a paste of limonite, kaolin, and calcite, in which occur many minute, angular bits of quartz and feldspar. Only a few of the feldspars show albite-twinning but their indices of refraction correspond to plagioclase. The twinned varieties have a composition approximating oligoclase or acid andesine.

The nature of the clastic material found in these rocks would indicate that they were eroded from the granites or diorites of the interior. At the southeastern side of Viti Levu, near Suva, a conglomerate, underlying flows of andesite and basalt, includes boulders of quartz porphyry and diorite. It is believed the two deposits represent a long period of erosion, in which the plutonic rocks of the center of the island were laid bare.

The marl from the coastal-plain series bears the popular name, "soapstone." It has a slate-gray color and becomes very smooth and oily when wet. Near Suva, lenses of coralliferous limestone are interbedded with this rock. When dry, the marl has little cohesion and breaks down readily. On exposure the ferrous oxide becomes oxidized and the rock assumes a yellowish brown color. It is rich in foraminifera and sometimes carries plant remains such as seed pods. Brady (1888) records that some of the foraminifera found by him in the marl, near Suva, were dredged by the "Challenger" in depths not less than 150 fathoms.

In 1907, specimens of the rock were sent to the Imperial Institute for examination. The specimens were labelled as follows:—

"A. Soapstone, Fiji. Surface, Government Office Yard."

"B. Soapstone, 6 feet below the surface, Suva."

Wright (1916) quotes the following description as given by the Imperial Institute.

"The two samples are similar in appearance and character. They were not soapstones, but may be classed as marls. They consist of volcanic dust, containing feldspar, hornblende, magnetite, and mica, together with a considerable quantity of the remains of calcareous and silicious organisms; some unbroken foraminifera occurred in both samples."

"Chemical examination of the samples gave the following results:—

	A	B
SiO_2	30.41	38.56
Al_2O_3	12.08	16.49
Fe_2O_3	5.40	7.54
MgO	6.95	5.78
CaO	19.24	12.77
K_2O	1.23	1.64
Na_2O	1.23	2.72
P_2O_5	trace	trace
NiO	trace	trace
H_2O+CO_2 (loss on ignition)	23.28	14.32
	99.82	99.82

It has previously been stated that the marls, near Suva, were probably laid down as a former delta-flat of the Rewa River. Their composition indicates that the river redistributed a large amount of ash and pumice, emitted by the coast volcanoes. The main mass of this rock, however, consists of silt, swept from the lateritized hills of the interior and deposited with calcium carbonate in the delta-area.

Conglomerate. Two varieties of conglomerate may be distinguished in Fiji. The one is a river-conglomerate and is poorly consolidated or has a small amount of siliceous cement. The other has a large amount of calcium carbonate associated with it, in the form of shells, corals, and cement. It was originally deposited along old shore-lines but now may often be found far inland. The first variety is not known in the smaller islands.

The river-conglomerates are often very coarse and contain boulders of andesite, basalt, and limestone 2 or 3 feet in diameter. Such deposits are well seen at the Na Roro bluffs 5 or 6 miles from the mouth of the Singatoka river, and are quarried for road-metal, a few miles up the Tamavua river, near Suva. They occur about the bases of eroded hills of basalt and andesite and, near Suva, are overlain by marls which contain occasional, larger boulders. Interbedded with the coarser conglomerates are layers composed of sand and gravels which have been washed from near-by agglomerates and are but slightly water-worn.

Two varieties of river-conglomerate are known. The first has pebbles and boulders of quartz-porphyry and diorite. It is found 2 or 3 miles from the mouth of the Visari river, at the western side of Suva harbor. It is overlain by lava flows of the second andesitic period and hence belongs to the period of erosion in which the folded sediments of central Viti Levu were deposited. Many of the pebbles in the conglomerate are sheared and it undoubtedly underwent the same folding which disturbed the marls of the interior.

The second variety of river-conglomerate consists predominantly of andesite and basalt débris and appears to have been eroded from the directly underlying agglomerates or flows. The matrix is often a reddish gray paste which resembles a redistributed ash. The Na Roro and Tamavua conglomerates belong in this class. The Na Roro deposit has pebbles and boulders of limestone, eroded from the limestones of the interior. The pebbles are usually much silicified. This type of conglomerate is often associated with a calcareous conglomerate, lying nearer the present shore-line and forming the basal member of the coastal-plain sediment.

Calcareous conglomerates unconformably overlie volcanic rocks in many of the islands. They are the basal members of the folded interior sediments, found 40 miles from the mouth of the Singatoka river, near Wai Mbasanga, and also of the coastal-plain series, exposed all along the southwestern coast of Viti Levu beneath the marls. Pebbles of volcanic rocks seldom form over 50 per cent of these deposits. Shell and coral waste with a calcareous cement compose the greater part of rock and, in thin sections, numerous foraminifera may be seen. By losing their coarser shell and coral material, these rocks grade upward into marls.

Limestones and Marbles. It is believed that all the limestones of Fiji are coralliferous. Some writers have spoken of the limestones of central Viti Levu and Vanua Mbalavu as massive and have inferred that they were formed by other agencies. Many of the interior limestones are so recrystallized that their structure is almost lost, and folding has transformed some of the limestone members to marble. But the writer found corals associated with the basal layers of this series and Mr. C. A. Holmes of the Lands Department, Suva, states that corals occur in the limestones of the inland valleys near the head of the Navua River.

The colors of the limestones are prevailingly cream-white, pink, and brick-red. An exceptional silver-gray limestone (weathering to a cream tint) was found near Lambasa, on the northern coast of Vanua Levu. Its color is the more remarkable since it is a very pure limestone and is burned for lime by the Colonial Sugar Refining Company.

Two partial analyses of the rock, supplied through the kindness of Manager Berry, are as follows: —

	Best	*Worst*
Insol	2.18	19.63
Sol. SiO_2	.46	
Al + Fe	1.37	5.54
CaO	52.96	37.68
MgO	.89	1.27
CO_2	41.20	29.60
H_2O	.58	4.46
Organic	.36	1.82
	100.00	100.00

The residual, hoodoo peaks of limestone which dot the landscape in certain parts of Fiji are composed of a cream-white or pink lime stone. At the surface this is cavernous but in depth most of these cavities are filled with crystalline calcite, not yet dissolved out. Even the pink varieties have only a slight amount of iron oxide which gives them their color, as shown by the analyses of Skeats (1903, p. 124). It is important here to note that selective solution probably accounts for the high content of magnesia in these residual peaks. Skeats found "the occurrence of dolomite at the summits of many of the islands. . . . significant."

The pink and brick-red colors are closely related and are due to the oxidation of the marl and volcanic waste deposited as a fine sediment about the coral heads. If the rocks are especially compact and do not permit the free circulation of aerated waters, the gray colors of the marl may be preserved. Examples of this were found at Lambasa.

The depth of the residual, brick-red soil which overlies the limestone is important as an indication of the amount of limestone lost by solution. For example, the depth of soil-cover at the summit of the limestone plateau of northern Vanua Mbalavu averages 2 to 3 feet. The average analyses of 17 limestones from the same locality show less than one tenth of one per cent of insoluble matter, (Skeats, 1903, p. 75). It follows that the amount of limestone lost by solution must be reckoned in hundreds of feet.

IGNEOUS ROCKS.

The following descriptions of the main igneous types refer to the various islands in the order: Viti Levu, Mbengha, Yasawa group, Vanua Levu, Taviuni, Lau Islands, and Kandavu. The petrologic problems involved will be briefly treated later.

It should be noted that in this paper the word "basalt" refers to a rock composed chiefly of augite and basic, plagioclase feldspar.

I. Rocks from Viti Levu.

1) *Tonalite.* Tonalite outcrops at Vunatoto, as low, rounded hills along the course of a branch of the Singatoka river, leading south from the village of Wai Mbasanga, central Viti Levu.

The rock is a holocrystalline, light, bluish-gray diorite of medium, coarse grain. It consists largely of feldspars 8 to 10 mm. long and 6 to 7 mm. wide, among which are disseminated irregular bits of quartz, hornblende, and biotite. A Rosiwal measurement gave the following proportions by weight:

Quartz	20.42	per cent
Plagioclase	73.44	" "
Magnetite	2.02	" "
Biotite	1.28	" "
Hornblende	2.84	" "
	100.00	" "

Pebbles in the conglomerate near Suva harbor are essentially similar, though richer in quartz.

The *quartz* has a wavy extinction due to strain and is often quite brecciated.

The *feldspars* are zoned and give evidence of intermittent growth. Their composition ranges from basic oligoclase to acid andesine or from $Ab_{78}An_{22}$ to $Ab_{63}An_{37}$. No orthoclase was found in the rock.

The *biotite* is chestnut brown in color.

The *hornblende* is a common variety, pleochroic, colorless // X, faint yellow // Y, and greenish yellow // Z.

The rock is very slightly altered and has a hypidiomorphic, granular structure. Its order of crystallization is: —.

magnetite,
biotite,
hornblende,
plagioclase,
quartz.

The chemical composition of the rock approaches that of a granite, and undoubtedly granites are associated with it in the field; but the dominance of andesine and the absence of orthoclase, lead the writer to designate it as tonalite.

Chemical analysis gave:—

SiO_2	70.00
TiO_2	0.30
Al_2O_3	14.72
Fe_2O_3	1.36
FeO	2.28
MnO	0.04
MgO	1.37
CaO	3.58
Na_2O	3.70
K_2O	1.68
H_2O	0.50
P_2O_5	0.06
	99.59

Norm	
Quartz	31.38
Orthoclase	10.01
Albite	31.44
Anorthite	16.96
Corundum	.51
Hypersthene	6.04
Magnetite	2.09
Ilmenite	.61
Apatite	.31
Water	0.50
	99.85

Specific gravity at 20°C = 2.675

Its position in the norm classification is, therefore:—

Class I	Persalane
Order 4	Britannare
Rang 3	Coloradase
Subrang 4	Yellowstonose.

Of the rocks classified by Washington (1903, pg. 191) under this system, a quartz-diorite from Aruba Island, West Indies is most closely allied to the Fiji type.

2). *Dioritic Gabbro.* Immediately back of the village of Waimbasanga low, rounded hills of gabbro rise to heights of 75 to 100 feet above the level of the Singatoka river. The relation of the gabbro to the granite is not exactly known. As one passes further south the gabbro disappears and diorites and granites outcrop. The textural similarity of these rocks leads to the belief that they are transitional into one another.

A Rosiwal measurement of the rock gave the following result.

Labradorite	62.85	per cent
Amphibole	27.90	" "
Magnetite	9.01	" "
Titanite	.24	" "
	100.00	" "

The feldspar shows pericline and albite twinning. It is zoned and has a composition varying from $Ab_{50}An_{50}$ to $Ab_{40}An_{60}$.

The amphibole is uralitic, probably derived from pyroxene, though none of the latter mineral remains. It is sometimes in crystals of considerable size but more often forms a felted mass of minute shreds.

The rock is very fresh in appearance and has a hypidiomorphic, granular structure. Its order of crystallization was probably as follows:—

titanite,
magnetite,
augite,
feldspar,
amphibole.

3). *Aporhyolite or Quartz porphyry.* Aporhyolites were not found in place in Viti Levu. The rocks to be described occur as pebbles and boulders in the conglomerate described from the Visari river, near Suva.

Three varieties are known. They are very dissimilar in appearance, due to recrystallization and crushing.

Variety 1, a glassy, slate-black type, is the freshest of these rocks. Grains of quartz and feldspar occur in a glassy, somewhat spherulitic ground-mass. The quartz phenocrysts occur as amoeboid, resorption forms. The feldspar phenocrysts are slightly zoned and average oligoclase in composition.

Variety 2 of a light gray color has similar phenocrysts, but its ground-mass is entirely recrystallized. The spherulitic forms are sometimes discernible but often the quartz fibers have enlarged themselves, forming distinct crystals. There is also a semblance of myrmekitic structure as reaction rims about the large quartz phenocrysts.

Biotite is found in scattered bits through the rock.

Variety 3, a light yellowish-gray rock, has undergone a considerable amount of shattering due to pressure. It is practically the same as variety 2. Its yellowish tint is due to a large amount of epidote scattered through, and veining, the ground-mass. The spherulitic structure is still preserved.

4). *Feldspar Porphyrite.* The rock to be described occurs as flows overlying the gabbro back of Waimbasanga, Singatoka river. It represents the first period of andesitic activity in Viti Levu.

The porphyrite is dark, slate gray in color, holocrystalline, and very fine-grained. Only occasional small phenocrysts of feldspar (2 to 3 mm. in diameter) are visible. They are indistinct, since they have the same color as the ground-mass. The rock appears fresh in the hand specimen but under the microscope is seen to be much recrystallized and metamorphosed. Considerable deposits of chalcopyrite are associated with the rock.

Augite may have formed a part of this rock at one time but no trace of it is now present. Actinolite is found in felt-like masses throughout the rock and occurs as needles in the feldspar, clouding the crystals.

The ground-mass of the rock is a complex of fibrous actinolite with laths of labradorite, Ab_{50} An_{50}, and grains of epidote and magnetite.

5) *Olivine Basalt from the Tamavua River.* Basaltic boulders occur in the conglomerate which forms the basal member of the coastal-plain series along the Tamavua river, near Suva. As basalts cut this series farther west, it is considered that the rock here described belongs to an earlier date than the last basaltic eruption and is probably contemporaneous with the second andesitic period.

The basalt is greenish black in color, compact, and recalls a porphyritic diabase.

The phenocrysts are olivine and labradorite, Ab_{40} An_{60}, with a few augites. Augite, labradorite, magnetite, and secondary minerals compose the ground-mass, which has an ophitic structure.

6) *Olivine Basalt from Lautoka.* Masses of greenish-black olivine basalt occur as residual boulders on the late-mature hills about Lautoka, on the western side of Viti Levu.

The rock is holocrystalline and very fine-grained. The phenocrysts in the rock consist of stubby, euhedral augite (4 to 5 mm. long) and rounded grains of zoned plagioclase, $Ab_{25}An_{75}$ to Ab_7An_{93}, (2 to 3 mm. long) with many olivine crystals.

The ophitic ground-mass is composed of olivine, augite, feldspar and abundant minute flecks of magnetite. Serpentine is secondary after the olivine.

The following analysis shows that the basalt is quite basic in composition.

SiO_2	47.36
TiO_2	0.85
Al_2O_3	19.38
Fe_2O_3	3.60
FeO	6.13
MnO	0.11
MgO	5.31
CaO	10.54
Na_2O	2.69
K_2O	1.74
H_2O	2.20
P_2O_5	0.19
	100.10

Norm	
Orthoclase	10.01
Albite	20.96
Nephelite	1.14
Anorthite	35.58
Diopside	12.82
Olivine	9.76
Magnetite	5.34
Ilmenite	1.67
Apatite	.31
	97.59
Water	2.20
	99.79

Specific gravity at 20°C = 2.855
Its position in the norm classification is: —

Class II	Dosalane
Order 5	Germanare
Rang 3	Andase
Subrang 4	Andose

7) *Olivine Basalt from Na Sana Sana.* The basalt, here described, occurs as a dike, 10 to 15 feet in width, in the elevated coralliferous limestone near Na Sana Sana, southwestern coast of Viti Levu.

The rock is greenish black in color, holocrystalline and somewhat vesicular. Calcite fills the vesicles. The phenocrysts of augite are in minute needles, while the feldspars ($Ab_{40}Au_{60}$) are in laths 4 to 6 mm. in length.

There are many irregular areas which appear to represent decomposed olivine. Chlorite, serpentine, epidote, and quartz are secondary constituents of the ophitic ground-mass. The alteration has been hastened by the action of sea-water.

The rock has inclusions of limestone. Near these inclusions there is a large amount of epidote and chlorite. The feldspar associated with the contact is more acid andesine, approaching oligoclase.

II. Rocks from Mbengha.

A considerable collection of rocks was made both from the sea-coast and from the hills of Mbengha. Eight of them were studied and it was found that they were all basalts. They fall into three groups. A typical specimen from each group will be described.

1. *Basalts composed chiefly of Augite and Feldspar.* It has been stated in the section giving the descriptive geology of Mbengha that the western side of the island is composed of flows which are little dissected. These flows are characterized by their lack of olivine. Specimens were collected from Ravi Ravi, from west of Wai Somo and from the top of the highest hill, the Beacon. Another specimen came from a dike cutting an olivine basalt at the southeastern side of the island, Ndakuni.

These rocks vary in appearance accordingly as they are holocrystalline or vitrophyric. The vitrophyric varieties are dark gray to black in color while the holocrystalline, diabasic varieties are greenish black.

One of the vitrophyric varieties has augite (diallage) and feldspar phenocrysts, in crystals 5 × 3 mm. in size, abundantly scattered through a glassy paste. Another is vesicular and the phenocrysts are so minute in size that they are indistinct in the slate-gray ground-mass.

The holocrystalline variety is very fine-grained, with minute needles of feldspar showing fluidal arrangement about an occasional augite phenocryst, 3 to 4 mm. in diameter.

The feldspar is almost always zoned and varies from acid to basic labradorite ($Ab_{50}An_{50}$ to $Ab_{25}An_{75}$). The feldspar of the ground-mass is usually a medium labradorite ($Ab_{40}An_{60}$).

2. *Basalts composed chiefly of Augite and Feldspar with Olivine.* The basalts characterized by olivine were collected from the southeastern or deeply dissected side of Mbengha, at Ndakuni and Ndakuimbengha.

They are very similar in general appearance to the types just described; though a glassy ground-mass appears in only one specimen. The typical rock is greenish black in color, compact and porphyritic in structure. The euhedral olivine phenocrysts are 8 to 10 mm. in diameter. The augite phenocrysts, in cases corroded, are about the same size or smaller. Zoned labradorite, ($Ab_{45}An_{55}$ to $Ab_{30}An_{70}$) is present but is often indistinct in the hand specimen. The groundmass is usually ophitic.

3. *Basalt composed of Augite and Feldspar with Hornblende.* Somewhat east of the center of the southern coast of Mbengha, a considerable bay indents the island. The town of Natheva lies at the head of the bay. Near its center and around its sides there outcrops a porphyritic hornblende basalt. The hornblende phenocrysts are largest (8 to 12 mm. long) at the east side of the bay and decrease in size to the west. The other phenocrysts are euhedral augite and labradorite, $Ab_{40}An_{60}$. The augite occurs in sharply euhedral crystals, showing the forms (001), (010), (100) and (011). The crystals are elongated parallel to c. The hornblende is a basaltic variety, pleochroic, chestnut-brown to yellow. The crystals are surrounded bq an opaque rim of magnetite with some augite.[2]

III. ROCKS FROM THE YASAWA GROUP.

Very few of the Yasawa Islands were visited. Volcanic rocks were collected from but two islands, Nathula and Arawa, a small island just west of Yasawa-i-lau.

Nathula yields only basalts of quite uniform composition. Arawa is composed of agglomerates. All the regular boulders from the agglomerate appear to be very similar. The specimen collected was a hornblende andesite.

1. *Basalt.* The specimen was collected from a flow interbedded with agglomerates near sea-level at the southwestern corner of Nathula.

The rock is greenish black in color, holocrystalline and porphyritic.

---

[2] Cp. Guppy, 1903, p. 306.

The phenocrysts of augite and zoned labradorite, $Ab_{42}An_{58}$ to $Ab_{26}An_{74}$, are small and about equal in size (2 to 3 mm. in diameter). The ground-mass forms about 80 percent of the rock which is fresh and above the average in weight. A few small vesicles are present. The ground-mass is ophitic; it bears magnetite and a little serpentine.

The chemical composition is:

SiO_2	50.06
Al_2O_3	19.38
Fe_2O_3	1.83
FeO	5.54
MgO	6.53
MnO	0.47
CaO	12.06
Na_2O	1.16
K_2O	0.93
H_2O (below 100°C)	1.14
H_2O (above 100°C)	0.37
CO_2	0.31
Total	99.78

Specific Gravity at 20°C = 2.808

Analyst, L. F. Hamilton.

Norm

Quartz	2.88
Orthoclase	5.56
Albite	9.96
Anorthite	44.76
Diopside	12.36
Hypersthene	19.60
Magnetite	2.55
	97.67
Water	1.51
CO_2	0.31
Total	99.49

Its position in the norm classification is:—

Class III	Dosalane,
Order 5	Germanare,
Rang 4	Hessase,
Subrang 3	Sodipotassic (unnamed).

Washington, in Professional Papers, Nos. 14 and 28, of the U. S. Geological Survey, reports no basalts having analyses similar to the above.

2. *Hornblende Andesite.* The andesite was found as a boulder in an agglomerate interbedded with ash on Arawa Island, just west of Yasawa-i-lau. This island has an area of but little over an acre.

The rock is light gray in color, with a brownish tinge due to weathering. It has phenocrysts of hornblende in lath-like forms, 4 to 5 mm. long. The zoned phenocrysts of andesine (Ab_{72} An_{28} to Ab_{60} An_{40}) are 3 to 4 mm. long and 2 mm. wide. The partly glassy ground mass is greenish gray in color; its feldspar is oligoclase. The hornblende occurs as euhedral crystals pleochroic, yellow to dark olive green. The mineral has no reaction rim of magnetite such as is common to the hornblende andesite of Kandavu and Vanua Levu.

IV. Rocks from Vanua Levu.

A. SUMMARY OF THE PETROGRAPHY OF VANUA LEVU AS GIVEN BY GUPPY.

Plutonic Rocks. Three varieties of plutonic rocks are listed by Guppy from seven different localities. All these localities lie along a mountainous ridge, running parallel to Natewa bay, i. e. in a N. E.–S. W. direction.

Hypersthene gabbros or norites are common throughout the district. A hornblende gabbro is described from the extreme southern end of the range and diorites were found in relations which indicate a close association between the two rock types.

Throughout the larger part of Vanua Levu, plutonic rocks are, therefore, very uncommon. They are not found west of a line connecting Savu Savu Bay and Lambasa, nor east of Natewa bay.

Volcanic Rocks. The volcanic rocks of Vanua Levu are grouped by Guppy into an elaborate classification of which the following members are most important:—

olivine basalts,
basaltic augite andesites,
hypersthene-augite andesites,
hypersthene andesites,
hornblende-hypersthene andesites,
dacites,
oligoclase trachytes,
quartz porphyries.

Olivine basalts compose the wide cone at the extreme southwestern end of Vanua Levu, known as Mount Seatura. The flow rocks forming the low lands west of this area are basaltic augite andesites. It is important to note that Guppy (1903, pp. 62–63) speaks of Mount Seatura as a well preserved volcanic cone, having slopes of 3 to 4 degrees which are, in certain cases, unscarred by subsequent erosion. It would appear that this mountain represents a comparatively late period of volcanic activity.

Excepting the region of basalts, just referred to, and another district underlain by rhyolitic types, the volcanic rocks of the rest of the island are prevailingly andesites and are characterized by the mineral hypersthene. Hypersthene-augite andesites are widely distributed from the Mbua district at the extreme western to Kimbalau point at the extreme eastern side of the island.

In a class called acid andesites, Guppy includes hypersthene andesites, hornblende-hypersthene andesites, and quartz-hornblende-hypersthene andesites or dacites. The hornblende of many of these andesites has reaction rims of magnetite and augite such as are common in the hornblende andesites of Kandavu and Mbengha. These rocks are said to "compose in mass, numerous isolated hills that rise up in the interior of the central portion of the island. Such hills, or mountains, as they might be often termed, usually attain a height of from 700 to 1200 feet above the surrounding country, and possess precipitous slopes and frequently perpendicular cliff-faces." From this description it would appear that andesites have been more deeply eroded than the basalts.

Hypersthene andesites are especially common at the northwestern side of the Wainunu tableland in west-central Vanua Levu, also in the district between Savu Savu and Natewa Bays.

Hornblende-hypersthene andesites occur north and northwest of the Wainunu tableland and, in general, are closely associated with the hypersthene andesites. In fact, all the hypersthene rocks grade into each other, from augite andesites with little hypersthene to hypersthene andesites and hornblende andesites with little augite. Hypersthene-bearing dacites are reported from the northwestern slope of the Wainunu tableland.

The district, east of Lambasa, along the northern coast of Vanua Levu, is characterized by rhyolitic rocks. In general the northern half of the peninsula, north of Natewa Bay, and, as well, the whole end of the peninsula near Undu Point, are composed of these rocks. The boundary, between the hypersthene andesites to the southwest and the rhyolites to the northeast, is an irregular line. Guppy does not state the relative ages of these rocks. The writer formed the opinion, from a study of the district east of Lambasa, about Mount Avuka, that the rhyolites were the first to be extruded. Oligoclase trachytes occur at the extreme northeastern end of Undu Promontory in association with quartz porphyries. Along the northern coast pumice-tuffs are most frequently found.

B. DESCRIPTION OF ROCK TYPES COLLECTED BY THE WRITER.

The writer was able to visit but a few places in Vanua Levu and hence can add little to the work already done by Guppy. The facts concerning rock distribution coincide with those already outlined. Rocks from four districts only will be described.

1. *Rocks from the Mbutha Bay District.*

a. A porphyritic, greenish-gray *basalt* was collected from a sill in the agglomerates which, with ash-beds, form the country rock of most of the district about Mbutha Bay. The exact locality lies midway between Mbutha and Natewa Bays at an elevation of above 1700 feet.

The feldspar phenocrysts usually have the composition of medium labradorite ($Ab_{40}An_{60}$), but a few are zoned, showing an outer zone of andesine, ($Ab_{58}An_{42}$), an intermediate zone of acid labradorite, ($Ab_{45}An_{55}$), and an inner zone of anorthite (Ab_5An_{95}).

The ground-mass is diabasic.

b. Hypersthene basalt was found in a boulder of an agglomerate on the south bank of the Mbutha River, 1¼ miles from its mouth. The rock is grayish white in color, compact, and finely granular. The dark phenocrysts are chiefly hypersthene; a few small brown hornblendes may be seen. Beautifully zoned feldspars abound. They consist of four layers, an outer of acid andesine, ($Ab_{63}An_{37}$), the next of basic andesine, ($Ab_{55}An_{45}$), which also forms the innermost zone, and a third of basic labradorite, ($Ab_{28}An_{72}$).

The ground-mass has a trachytoid texture and consists of feldspar with abundant minute grains of magnetite. There is some evidence of devitrification.

2. *Rocks from the Lambasa District.*

a. Gabbro. Gabbro forms a low, rolling topography along the divide between the Ngawa and Mbutha Sau rivers just east of Lambasa. The eroded gabbro surface was submerged and covered by marine ash-deposits and basaltic flows; subsequent uplift permitted further erosion to uncover the gabbro.

The specimen to be described was collected from the crest of the divide, at an elevation of 1500 feet. It is a medium-grained, iron-gray rock consisting of feldspar and augite. The laths of feldspar are 3 to 4 mm. long and 1 to 2 mm. wide and between them in diabasic arrangement is a felted mass of fibrous augite and hornblende. The rock breaks irregularly and is but slightly altered.

The weight proportions of the essential minerals are: —

Augite and uralitic hornblende	14.3
Feldspar	84.8
Iron ore	.9
	100.0

The larger part of the feldspar is a medium labradorite, ($Ab_{40}An_{60}$). Zoned feldspars show the following composition, passing from the inner to the outer zones: —

Anorthite	Ab_5An_{95}
Basic labradorite	$Ab_{25}An_{75}$
Medium labradorite	$Ab_{40}An_{60}$
Andesine	$Ab_{65}An_{35}$

The augite is in irregular, shattered bits, some of which are included in the outer zones of the feldspars.

The gabbro has the following chemical composition: —

SiO_2	50.01
TiO_2	1.01
Al_2O_3	19.33
Fe_2O_3	1.85
FeO	6.26
MnO	.21
MgO	3.51
CaO	12.38
Na_2O	2.13
K_2O	0.18
P_2O_5	trace
H_2O+	1.85
H_2O-	1.55
Total	100.27

Norm	
Quartz	5.40
Orthoclase	1.11
Albite	17.82
Anorthite	42.53
Diopside	15.62
Hypersthene	9.78
Magnetite	2.78
Ilmenite	1.98
Water	3.40
Total	100.42

Specific Gravity at 20°C = 2.753
Analyst — P. C. Voter.

Its position in the norm classification is:—

Class III	Dosalane,
Order 5	Germanare,
Rang 4	Hessase,
Subrang 3	Hessose.

b. Basalt. Porphyritic basalts are found throughout the Lambasa valley. They overlie the gabbro just described and form agglomerates composing the bulk of the peaks of the Three Sisters and Mount Avuka. The specimen to be described was taken from a limestone-covered ridge, jutting out into the delta plain a mile and a half northwest of Lambasa.

Phenocrysts of diallage are associated with more abundant phenocrysts of plagioclase ($Ab_{60}An_{40}$, to $Ab_{40}An_{60}$) in the rock. Due to decomposition, epidote is abundant in the ground-mass associated with feldspar and augite. Magnetite dust is also present in large amount. The structure of the ground-mass is diabasic.

The feldspars are zoned, but difficult to determine because of decay. The average feldspar approaches a basic andesine and hence the rock in places verges into basaltic andesites.

c. Foraminiferal Basaltic Ash. A number of hills rising to an elevation of approximately 160 feet dot the Lambasa flood plain. They are composed of fine, greenish ash of basaltic composition, doubtless allied in origin with the basalt of the adjacent hills.

The ash is well cemented into a compact, greenish-gray rock of very fine texture. The grain is, however, coarser than that of the marls of the Suva district. Foraminiferal tests indicate that the deposit was laid down beneath the sea.

d. Andesitic Porphyrite and Pitchstone. The shore east of the Mbutha Sau river, near Lambasa, is composed of a fine, grayish white, rhyolitic ash. The ash is occasionally intruded by slightly vesicular, porphyritic dikes, having pitchstone contact-facies against the rhyolite. The dike rock described below occurs on Salia Levu Point, near Wavu Wavu.

The rock is slate-gray in color, massive, and shows an occasional minute feldspar in an aphanitic ground-mass.

The feldspar phenocrysts have the composition, oligoclase-andesine, ($Ab_{70}An_{30}$), and the ground-mass is composed of feldspar and glass with a hyalopilitic texture.

3. *Rocks from the Savu Savu Bay District.*

a. Hypersthene Basalt. Along the seaward side of the peninsula forming the southeastern boundary of Savu Savu Bay, there are several masses of elevated limestone. The largest mass is cut by a river-valley broadening toward the sea. The western remnant, near the village of Nandi, is underlain by a basalt flow and calcareous agglomerate, passing upward into conglomerate and the coralliferous limestone mentioned. The change from volcanic activity to the deposition of coralliferous limestone was accomplished in a comparatively short time. Specimens were collected from the underlying flow and from a boulder enclosed in the limestone. They were found to be identical. The specimen from the flow will be described.

The rock is iron-black in color and shows needles of feldspar (5 to 8 mm. in length) abundant in an aphanitic ground-mass. Occasional phenocrysts of augite are found and an inclusion of silicified limestone.

All the phenocrysts are euhedral or subeuhedral. An older generation of feldspar phenocrysts is much clouded by inclusions of glass. They show renewed growth. The augite phenocrysts are on the contrary resorbed. One augite crystal has a core of hypersthene.

The zoned feldspars show the following composition: —

Outer zone.........andesine, $Ab_{63}An_{37}$
Central zone.......labradorite, $Ab_{47}An_{53}$
Inner zone.........basic labradorite, $Ab_{35}An_{65}$

The average feldspar is medium labradorite.

The structure of the ground-mass is hyalopilitic.

b. Basalt. The ridge between Savu Savu and Natewa Bays near Valanga is composed largely of agglomerates interbedded with flows. The agglomerates are olive-gray in color and are composed of ash with angular bits of olivine basalt. On the other hand, the specimens of flow rock lack olivine.

The flow rock is slate-gray in color and consists of abundant, small, augite phenocrysts, 2 to 3 mm. in length, set in an aphanitic groundmass. Feldspar (Ab_{45} An_{55}) laths of the same size are so like the ground-mass in color that they are indistinct in the hand specimen.

4. *Rocks from the Divide between the Lambasa and Savu Savu Bay Districts.*

a. Basaltic Conglomerate. The crest of the divide between Lambasa and Savu Savu Bay is formed of conglomerate rocks containing rounded pebbles of basalt 1 to 2 cm. in diameter. Some of the pebbles are green, others slate or brick-red color according to their degree of alteration. Their structures vary from porphyritic through glassy to scoriaceous. They are set in an ashy paste. Lower down on the slopes of the ridge, the paste becomes calcareous and the pebbles smaller. Foraminiferal tests and even small shells are sometimes found. It would appear that the present crest of the ridge is not far from the strand-line of the ancient volcanic period. The sediments dip gently to the southwest.

The microscope shows that all the pebbles of the conglomerate are basaltic. The vesicles of the rocks from the crest are filled with chalcedonic amygdules while the lower rocks have calcareous fillings. Olivine and hypersthene are the prevailing ferro-magnesian minerals; the feldspar is a medium to basic labradorite.

b. Gabbro Porphyrite. Descending the crest of the divide on the way from Savu Savu Bay to Lambasa, the first 500 feet is very precipitous. Thereafter the paths along the stream beds are gentler. Near the intersection between the two slopes there are waterfalls at certain dikes which resist erosion better than the adjoining conglomerates. Specimens of the dikes were collected from an altitude of 1100 feet and 800 feet. They proved to be very similar. A specimen from the lower level will be described.

The slightly vesicular rock is iron-gray in color, showing phenocrysts of feldspar, 3 to 4 mm. in length, evenly disseminated in a finely crystalline, felty ground-mass.

Feldspar phenocrysts are very abundant. Very few augite crystals are present. The ground-mass has a typical diabasic texture of coarser grain than the average basalt, hence the rock is referred to as a gabbro porphyrite. The feldspars are usually not zoned but are in laths (as labradorite, Ab_{50} An_{50}). One or two zoned specimens were found having the composition:—

Outer zone, oligoclase, $Ab_{75}An_{25}$,
Middle zone, andesine, $Ab_{58}An_{42}$,
Inner zone, labradorite, $Ab_{43}An_{57}$.

V. Rocks from Taviuni.

Thirteen rocks were studied from the collections made in Taviuni. Eleven are olivine basalts; the other two contain basic andesine and are closely related types. Most of the specimens came from the western side of the island, but a few were collected from the eastern shore at its northern and southern extremities. The small island of Vunimbani, off the northeastern shore, is capped with a water-laid ash deposit of fine texture, 20 to 30 feet in thickness. Beneath the ash lies a vesicular olivine basalt closely related to the basalts of the adjacent shore of the main island. The two types have acid labradorite merging into andesine as their feldspar.

The textures of the basalts of Taviuni are generally diabasic; in two cases the ground-mass has pilotaxitic texture while a third rock shows a trachytoid arrangement of its feldspar needles.

The rocks were collected from widely separated localities and are considered to be typical. Two varieties only will be described.

(1) *Andesitic Basalt.* The northeastern slopes of Taviuni are covered at intervals by a series of recent flows emanating from two well preserved, accessory cones. The flows rest upon a lateritized surface of vesicular basalt having a composition very similar to the more recent lavas. The specimen described is from a recent flow at Nangasau.

The rock is fresh, highly vesicular, slate-gray in color and has a cryptocrystalline ground-mass in which are many minute phenocrysts of feldspar and olivine. The phenocrysts are hardly noticeable in the hand specimen.

The olivine phenocrysts are euhedral and larger, as well as more abundant, than the plagioclase phenocrysts. The plagioclase phenocrysts are zoned and have a composition varying from $Ab_{55}An_{45}$ to $Ab_{50}An_{50}$ or from basic andesine to acid labradorite.

The ophitic ground-mass consists of olivine and plagioclase with abundant minute bits of iron ore.

(2) *Olivine-gabbro Porphyrite.* Near the center of Taviuni, back of the village of Somo Somo, there is an extinct crater whose walls have not yet been breached by erosion. From the outer slope of the western walls, at an elevation of approximately 4000 feet, the rock to be described was collected.

It is a fresh, massive, slate-gray rock containing abundant phenocrysts of feldspar (8 to 10 mm. in diameter) with augite and olivine phenocrysts of the same size but less abundant.

The phenocrysts are large augite crystals, zoned feldspars, and less numerous olivine crystals.

The feldspar phenocrysts are beautifully zoned, showing an outer zone of acid labradorite, $Ab_{48}An_{52}$, an intermediate zone of andesine, $Ab_{79}An_{21}$, and an inner zone of labradorite, $Ab_{42}An_{58}$.

The diabasic ground-mass, composed of plagioclase, olivine, and augite, is much more coarsely crystalline than that for the average basalt and the rock for this reason has been referred to as a porphyrite.

VI. Rocks from the Lau Islands.

Volcanic rocks were collected from the following islands of the Lau Group. The specimens will be described from the islands in the order given:

Vanua Mbalavu,
Yanu Yanu,
Susui,
Munia,
Thikombia-i-lau,
Kanathea,
Tuvuthá,
Lakemba,
Ono-i-lau,
Kambara,
Moala.

Throughout, the order of description will be first andesites, and then basalts. No vesicular types of the andesite were found on Vanua Mbalavu. In general, the andesites and basalts belong to two different periods. Though basalts may occur in the andesitic period, such basalts are not known to contain olivine. The andesites or andesitic basalts were extruded before the deposition of the elevated limestones; the olivine basalts after their deposition.

Vanua Mbalavu.

1) *Andesite from southwestern side.* The andesite was found as a small, laccolithic mass injected into tuffs and agglomerates and exposed in a sea-cliff at the southern side of a point of land just south of Ndaku-i-Loma Loma.

The rock is oily, dark gray in color, holocrystalline and without noticeable phenocrysts in the hand specimen. In thin section a very few small phenocrysts of andesine ($Ab_{59}An_{41}$) may be seen. These phenocrysts are set in a very fine paste of augite and feldspar, showing a pilotaxitic texture. There is an abundant sprinkling of fine bits of magnetite and secondary epidote has developed.

2) *Andesite from the western side.* The andesite in question came from the coast near the roadstead indicated on the charts. It occurs in cliffs cut about the bases of mature hills.

It is a slate-black, porphyritic rock. Abundant large phenocrysts of feldspar, 10 to 13 mm. in diameter, and less conspicuous augites are set in a ground-mass consisting largely of glass with disseminated augite, feldspar, and magnetite.

The feldspar phenocrysts are very irregularly intergrown and twinned. Most of them are zoned and show a composition varying from $Ab_{65}An_{35}$ to $Ab_{47}An_{53}$. The feldspar of the ground-mass is andesine, $Ab_{65}An_{35}$.

3) *Basalt from Koro Mbasanga.* Koro Mbasanga is the highest peak in Vanua Mbalavu. It rises in the north central part of the island. Two specimens of basalt were collected; one from the floor of the breached crater and the other from a spur ridge south of the summit. Their textures vary but their composition is similar. The specimen from near the summit is holocrystalline and fine-grained with very small phenocrysts. The other has larger phenocrysts, the olivine, especially, being distinct. The latter specimen will be described.

The rock is gray-black in color, holocrystalline, and porphyritic. The feldspar phenocrysts are 2 to 3 mm. in diameter while those of olivine are 5 to 8 mm. in diameter. Abundant large phenocrysts of olivine and smaller ones of augite and feldspar appear in the slide. Augite, feldspar, pyrite, magnetite, and a little olivine compose the ophitic ground-mass. The feldspars are zoned labradorites, varying in composition from $Ab_{43}An_{57}$ to $Ab_{38}An_{62}$.

4) *Vesicular basalt from Mua Mua.* On the western side of Vanua Mbalavu, somewhat south of the center of the island, there is a mangrove swamp. At its northern edge the swamp abuts directly against rather steep slopes of sub-Recent, porphyritic lavas. These lavas are fresher than most of the other rocks of the island, in spite of the fact that they are very vesicular.

The olivine phenocrysts are large and euhedral. The feldspar, a medium labradorite, ($Ab_{40}An_{60}$) occurs in short, stubby laths. The ground-mass is largely feldspar with a few minute olivine crystals in the interstices. Some augite is also present.

5) *Basalt from the north side.* This basalt occurs within a valley in the limestone, 4 to 5 feet above sea-level, just north of the point forming the northern side of the bay at Dalithoni.

It is a fresh dark purple, vesicular rock, with a very fine holocrystalline structure. Phenocrysts of feldspar, 5 to 7 mm. in diameter, occur in an aphanitic ground-mass.

In thin-section an occasional augite phenocryst is seen to be associated with the feldspar. The ophitic ground-mass is largely composed of augite with disseminated feldspar crystals. Both generations of feldspar are labradorite, $Ab_{40}An_{60}$, though some of the crystals are zoned.

6) *Andesitic Basalt from Tota.* Tota is situated at the juncture of the volcanic rocks with the limestones on the northeastern shore of Vanua Mbalavu. Just south of the village low spurs from the volcanic hills jut out into the sea. To the northwest abrupt limestone cliffs rise from a narrow beach. Inland there is evidence that the limestone overlies the volcanic rocks. The andesite here described was collected from the volcanic spurs south of the village, but its relations to the limestone is uncertain. It is believed, however, to represent a flow from the basaltic cone of Koro Mbasanga rather than to be allied to the andesite underlying the limestone.

The rock is reddish brown in color, holocrystalline and fine grained. Phenocrysts of feldspar and diallage are evenly disseminated through the rock. Larger olivine phenocrysts are not so common. The ground-mass is composed of augite and feldspar in intersertal relation, associated with magnetite particles and some olivine.

The feldspars are zoned and show a composition varying from $Ab_{56}An_{44}$ to $Ab_{48}An_{52}$ or from basic andesine to acid labradorite. The texture of the ground-mass is coarser than that of the average rock studied. Minute inclusions which appear to be olivine are sometimes found in the feldspars.

The analysis of the basalt is as follows: —

SiO_2	55.75
Al_2O_3	16.53
Fe_2O_3	0.53
FeO	7.14
MgO	3.19
MnO	0.55
CaO	9.12
Na_2O	4.24
K_2O	0.95
H_2O (below 100°C)	1.04
H_2O (above 100°C)	0.51
CO_2	0.32
Total	99.87

Norm	
Quartz	1.50
Orthoclase	6.12
Albite	35.63
Anorthite	23.27
Diopside	18.62
Hypersthene	12.13
Magnetite	0.70
	97.97
Water	1.55
CO_2	0.22
Total	99.74

Specific Gravity at 20°C = 2.845
Analyst, L. F. Hamilton.

Its position in the Norm classification is: —

Class II	Dosalane,
Order 5	Germanare,
Rang 3	Andase.
Subrang 4	Andose.

Yanu Yanu.

1. *Andesite.* This rock forms dikes, 3 or 4 feet wide, cutting ash beds, on the eastern side of the island.

The rock is purplish brown in color. Phenocrysts of andesine, $Ab_{65}An_{35}$ to $Ab_{60}An_{40}$, in laths 3 to 4 mm. long, occur in a vitreous ground-mass, bearing microcrysts of feldspar.

2. *Olivine Basalt.* The island of Yanu Yanu rises in a cone, 270 feet high. Its main mass is made of the rock described below which was collected from the summit of the island.

The basalt is fresh, massive, nearly black, holocrystalline, and medium to fine-grained.

In thin section abundant small phenocrysts of olivine are seen with other phenocrysts of augite and feldspar. The ophitic ground-mass contains abundant augite, some olivine, considerable andesine, $Ab_{60}An_{40}$, and magnetite.

The analysis of the basalt is as follows: —

		Norm	
SiO_2	48.56		
TiO_2	2.40	Quartz	.78
Al_2O_3	16.30	Orthoclase	3.89
Fe_2O_3	2.04	Albite	17.29
FeO	8.61	Anorthite	33.36
MnO	0.10	Diopside	4.51
MgO	8.76	Hypersthene	29.87
CaO	8.22	Magnetite	3.02
Na_2O	2.04	Ilmenite	4.56
K_2O	0.70	Apatite	.62
H_2O	1.60		97.90
P_2O_5	0.30	Water	1.60
	99.63		99.50

Specific gravity at 20°C = 2.889

Its position in the Norm classification is, therefore:—

Class III	Salfemane
Order 5	Gallare
Rang 4	Auvergnase
Subrang 3	Auvergnose.

Basalts erupted from Kilauea, Hawaii in May, 1883, have a composition very similar to the basalt described above, (Washington, 1903, p. 337).

Susui.

1. *Andesite.* Andesite forms glassy flows, 8 to 10 feet thick, just northeast of the town of Susui. The flows strike about E–W and dip 30° S. They are vesicular near their top and elsewhere have a platy structure.

The rock is slate-black in color but often has a reddish tinge due to the formation of hematite. It is massive and porphyritic. The phenocrysts of andesine, $Ab_{63}An_{37}$ to $Ab_{59}An_{41}$, and augite are small (1 to 2 mm. in diameter).

The ground-mass is composed of minute laths of feldspar in a glassy matrix.

2. *Basalt.* Interbedded flows of basalt form a point at the extreme eastern end of Susui. The flows dip 25 to 30° S. W. The specimen to be described was collected near sea-level.

The fresh rock is slate-gray in color, massive and porphyritic. It is holocrystalline and very fine-grained.

The phenocrysts visible in the thin section are feldspar, olivine, and augite. The olivine phenocrysts are most abundant, though the feldspars are more distinct in the hand specimen. The feldspars are labradorite, $Ab_{40}An_{60}$ to $Ab_{25}An_{75}$.

There is very little olivine in the pilotaxitic ground-mass and the approximate proportions of feldspar and augite are 60 to 40.

Munia.

Olivine basalt. Massive flows, interbedded with ash and agglomerate deposits, form the abrupt slopes of the eroded crater of Munia. The writer collected five specimens from the flows and from boulders in the agglomerates. They differ only in structure. The rock to be described was taken from a flow in the east central part of the island at an elevation of 200 feet.

The basalt is slate-gray in color and fine-grained. An occasional feldspar phenocryst, 4 to 5 mm. in length, may be seen, but usually the feldspar is in the form of minute needles associated with small augite crystals, 1 to 2 mm. in diameter. The rock is very fresh and breaks with conchoidal fracture.

Phenocrysts of augite, olivine and plagioclase feldspar are abundant in the thin section. The ground-mass, with occasional traces of a diabasic texture, is composed of augite, olivine, feldspar, and glass with abundant magnetite dust.

The feldspar phenocrysts show zonal inclusions and frequently are zoned, having the composition, $Ab_{42}An_{58}$, labradorite, and $Ab_{23}An_{77}$, bytownite.

Thikombia-i-lau.

1. *Andesitic Basalt.* A little to the east of the extreme southwestern point of Thikombia-i-lau is a point of land, built up of a coarse agglomerate. Cutting the agglomerate is a dike of basalt, 5 to 6 feet in width. This intrusive is fine-textured and porphyritic. It is fresh, dark gray, almost black, in color. Augite (diallage) and labradorite ($Ab_{40}An_{60}$) phenocrysts, 2 to 3 mm. in diameter, form 30 per cent of the rock. The structure of the ground-mass is hyalopilitic.

The chemical composition is as follows: —

		Norm	
SiO_2	58.30		
TiO_2	0.80	Quartz	12.36
Al_2O_3	17.10	Orthoclase	5.00
Fe_2O_3	2.10	Albite	31.44
FeO	5.58	Anorthite	27.52
MnO	0.08	Diopside	6.93
MgO	2.70	Hypersthene	10.74
CaO	7.40	Magnetite	3.02
Na_2O	3.72	Ilmenite	1.52
K_2O	0.83	Apatite	.31
H_2O	1.15		98.84
P_2O_5	0.22	Water	1.15
	99.98		99.99

Specific gravity at 20°C = 2.700

Its position in the Norm classification is: —

Class II	Dosalane,
Order 4	Austrare,
Rang 3	Tonalase,
Subrang 4	Tonalose.

The lavas of Bandai San, Japan, approach the composition of the basalt from Thikombia and also a lava from a volcano on New Britain Island, Pacific Ocean. The Bandai San lavas are described as andesites and undoubtedly the rock just described has a composition more closely allied to an andesite than to a basalt but since its feldspars are largely labradorite it is called a basalt. The lavas of Crater Lake, Oregon, are also similar to the rock here described.

2. *Vesicular Basalt.* This specimen was broken from an angular boulder in the agglomerate which constitutes a small cape near the middle of the south shore of Thikombia-i-lau.

The fresh basalt is a very spongy, vesicular type with fine vesicles. It is dark gray in color and porphyritic.

The feldspar phenocrysts are 2 to 3 mm., occasionally 8 to 10 mm., in diameter. They are zoned and the zones are frequently outlined by glass inclusions. They have the average composition of labradorite, $Ab_{45}An_{55}$ to $Ab_{40}An_{60}$. The augite is a diallagic variety.

The ground-mass has a hyalopilitic texture. Feldspar and augite, in the approximate proportion of 70 to 30, and abundant magnetite are present in the glass.

Kanathea.

Olivine basalt. Three specimens of basalt from Kanathea were examined. One came from sea-level at the northeastern side of the island; another was collected at an elevation of approximately 20 feet within the central valley; and a third was taken from the summit of a high cliff at the southern side of the central valley. All three have approximately the same composition. A typical specimen will be described. This rock occurs as a sill intruded into the agglomerate near sea-level.

It is very dark gray, massive, holocrystalline, and fine-grained. The augite and olivine phenocrysts are 4 to 5 mm. in diameter; the zoned labradorite phenocrysts ($Ab_{57}An_{43}$ to $Ab_{43}An_{57}$) are smaller. The ground-mass is diabasic.

Tuvuthá.

1. *Basalt.* The specimen to be described was collected from the lateritized summit of the central ridge of Tuvuthá near an isolated remnant of limestone, unconformably overlying the basalt.

The light, purplish gray, porphyritic basalt has zoned feldspar phenocrysts 4 to 5 mm. in diameter, the zones often outlined by inclusions of glass. The composition of the feldspar varies from a basic andesine to a basic labradorite, $Ab_{52}An_{48}$ to $Ab_{30}An_{70}$. The feldspar of the ground-mass occurs in small laths and appears to average a labradorite.

The phenocrysts of augite have the usual characteristics.

The structure of the altered ground-mass was originally vitrophyric-porphyritic.

2. *Olivine Basalt.* A point of land 60 to 75 feet high rises just south of the village of Tuvuthá. The seaward face of the hill is composed of a calcareous breccia. The specimen was taken from a fragment in the breccia.

The rock is dark gray in color, massive and porphyritic. The phenocrysts of augite and feldspar vary from 3 or 4 mm. to 8 or 10 mm. in diameter. They are accompanied by abundant olivine phenocrysts. The feldspar phenocrysts are not zoned. They have the composition of a medium labradorite, $Ab_{40}An_{60}$. The augite phenocrysts give evidence of a second stage in their growth.

The structure of the ground-mass is vitrophyric-porphyritic.

Lakemba.

1. *Andesite.* Just east of the village of Wathiwathi at the southeastern side of Lakemba, there is a point of land composed of agglomerates and flows. These are cut by a perpendicular dike 12 feet wide and very glassy near its edge. The specimen was collected from the glassy edge.

The andesite is jet black in color, aphanitic and slightly vesicular. It has the macroscopic appearance of a glass and breaks with a conchoidal fracture. Minute phenocrysts of feldspar, 1 mm. long, are disseminated through the glass. The rock is very slightly altered.

The phenocrysts are feldspar and augite. The feldspars are zoned and have the composition of andesine, $Ab_{63}An_{37}$ and $Ab_{56}An_{44}$. Carlsbad twins are frequent.

The glass of the ground-mass bears no augite, consisting only of a felt of feldspar needles with magnetite grains.

2. *Olivine basalt.* The government schoolhouse at Thoumbo stands on a low spur from the central hills. The spur has a veneer of limestone but, beneath, lies a series of flows and agglomerates which are deeply lateritized. The basalt was collected from a residual boulder about one hundred yards northeast of the schoolhouse.

The rock is dark gray in color, massive and coarsely porphyritic. Feldspar phenocrysts (labradorite, $Ab_{40}An_{60}$), 10 to 15 mm. in diameter, form 40 to 50 per cent of the rock. The rock is remarkable in having no augite phenocrysts. The olivines are small and scattering.

The ground-mass is an ophitic aggregate of minute crystals of augite and feldspar.

Ono Group.

1. *Vesicular andesite.* Ndoi consists of agglomerate and flows dipping north and northeast. Its summit, at an elevation of 279 feet, is composed of agglomeratic rocks. This specimen was broken there from a boulder in the agglomerate. The andesite has a spongy vesicular structure, with the vesicles elongated in the direction of flow. The rock is slate-drab in color.

The microscope shows that a glassy rim, altered to kaolin, surrounds the vesicles, between which is a mat of feldspar needles. The feldspar is a medium andesine, $Ab_{62}An_{38}$.

The ground-mass is hyalopilitic.

2. *Olivine andesite from Ndoi.* Interbedded lava flows stand up as hog-back ridges between ash and agglomerate deposits on the northwestern side of Ndoi. The specimen was collected from one of these flows.

The rock is highly vesicular and grayish brown in color. The feldspar phenocrysts are most abundant. They are of two generations. The first generation are large, zoned, and show inclusions of glass regularly arranged. Large augite phenocrysts are of the same generation. The second generation are smaller and show less distinct lines of growth. The zoned feldspars have the composition of medium andesine and acid labradorite, $Ab_{59}An_{41}$ to $Ab_{48}An_{52}$. Andesine occurs in the ground-mass.

Small olivine phenocrysts are scattered through the ground-mass and are associated with the second generation of feldspars.

The texture of the ground-mass, little else but a mat of feldspar, is pilotaxitic.

3. *Basalt.* The basalt in question was taken from a dike cutting the olivine andesite just described.

It is gray in color and slightly vesicular. There are no phenocrysts distinct in the hand specimen. The general structure of the ground-mass is pilotaxitic but near the vesicles it is hyalopilitic. The rock is chiefly composed of a mat of small labradorite ($Ab_{33}An_{67}$) needles with occasional phenocrysts of labradorite and rather rare phenocrysts of augite.

4. *Olivine andesite from Ono Levu.* The rocks of Ono Levu are very similar to those of Ndoi. The andesite to be described was collected from the outcrop of a flow, forming the summit of a flat hill at the northwestern end of the island.

The rock is slate-black to dark purple in color. It is massive and porphyritic, with phenocrysts of feldspar, 4 to 6 mm. in diameter, forming 30 per cent of its mass. Augite phenocrysts of a like size form 10 per cent of the rock.

The feldspar crystals are frequently zoned but vary only slightly in composition. They are a basic andesine, $Ab_{57}An_{43}$. The augite phenocrysts are twinned on the front pinacoid. There are very few olivine phenocrysts.

The ground-mass has a hyalopilitic texture but there is little glass present. Minute needles of feldspar form the larger part of its composition; magnetite is present.

The absence of abundant olivine phenocrysts in the rock reveals the fact that it is not very basic. This conclusion is borne out by the following analysis:—

SiO_2	52.08
TiO_2	1.40
Al_2O_3	17.86
Fe_2O_3	2.22
FeO	5.76
MnO	0.10
MgO	3.89
CaO	8.20
Na_2O	3.67
K_2O	2.07
H_2O	2.35
P_2O_5	0.36
	99.96

Norm	
Orthoclase	12.23
Albite	31.44
Anorthite	25.85
Diopside	9.98
Hypersthene	11.16
Olivine	0.17
Magnetite	3.25
Ilmenite	2.74
Apatite	0.93
	97.75
Water	2.35
	100.10

Specific gravity at 20°C = 2.792.

The position of the rock in the Norm classification is:—

Class II	Dosalane,
Order 5	Germanare,
Rang 3	Andase,
Subrang 4	Andose.

Kambara.

Olivine Basalt. A thick dike of olivine basalt has broken through the limestone at the northwestern side of Kambara and stands up in the hill Ndelai Yaloi. Several specimens of the rock were collected of which three were studied. One of these was collected at the lower contact of the dike, another was taken from the upper contact, while a third came from a zone some 15 to 20 feet from the upper contact.

The general characteristics of all these rocks are the same. They vary, however, in their texture and in the amount and variety of their phenocrysts. Near the upper contact the rock is very vesicular and has large vesicles 15 to 20 mm. in diameter. Here olivine phenocrysts are abundant but augite and feldspar phenocrysts are lacking. Towards the center of the dike, the feldspar and augite crystals increase in abundance and the vesicles become smaller.

The basalt from the top of the hill of Ndelai Yaloi will be described. The contact is 15 to 20 feet south of the summit.

The rock is drab-gray in color, very fine, even-grained and somewhat vesicular. Phenocrysts of olivine 5 to 8 mm. in diameter are seen but the small augite phenocrysts are less distinct.

Feldspar occurs only as fine needles in the ground-mass. It has the composition of basic andesine, $Ab_{60}An_{40}$.

The olivine phenocrysts are euhedral, but the augites are irregular and resorbed.

The intersertal ground-mass contains olivine, augite, and feldspar. Serpentine, kaolin and hematite have developed by weathering. The analysis of this rock is:

		Norm	
SiO_2	45.63		
Al_2O_3	15.56		
Fe_2O_3	3.12	Orthoclase	6.67
FeO	10.81	Albite	11.00
MgO	8.64	Anorthite	33.36
MnO	0.24	Diopside	20.38

CaO	11.52	Hypersthene	4.71
Na_2O	1.26	Olivine	18.06
K_2O	1.11	Magnetite	4.41
H_2O (below100°C)	0.65		98.59
H_2O (above 100°C)	0.80	Water	1.45
CO_2	0.40	CO_2	0.40
Total	99.74	Total	100.44

Specific gravity at 20°C = 2.948.
Analyst, L. F. Hamilton.

The position of the rock in the Norm classification is:—

Class III	Salfemane,
Order 5	Gallare,
Rang 4	Auvergnase,
Subrang 3	Auvergnose.

The basalt from Kambara resembles a basalt from Kilauea, Hawaii, described by J. D. Dana in the American Journal of Science, (3) volume 18, page 134, (1879).

Moala.

Olivine basalt. The writer did not visit the island of Moala but Dr. St. Johnston of Loma Loma kindly presented a few specimens. They are all typical olivine basalts, differing only in structure.

V. ROCKS FROM KANDAVU.

All the specimens from Kandavu were collected during a rapid survey of the southern coast of the island, east of Vunisea. A large number of villages were visited. Most of them are situated on spur hills, 60 to 75 feet high, along the coast. Usually these hills were deeply lateritized and the specimens were collected from residual boulders, lying on the surface.

1) *Trachytoid Andesite.* The specimen was collected from a residual boulder on a lateritized hill, 75 feet high, near the village of Na Vora.

The rock is light yellowish gray, holocrystalline and fine-grained. It is nearly devoid of femic minerals. A few small phenocrysts of augite and feldspar may be seen under the microscope, but the ground-mass forms, on an average, 90 per cent of the rock. The feldspars forming the ground-mass are larger than usual and show a flow arrangement with small, rounded augites in the interstices. The feldspar has the composition of a basic andesine or acid labradorite, $Ab_{52}An_{48}$.

The texture of the ground-mass is exceptional for Fijian lavas and may be called trachytoid.

2) *Hornblende Andesite.* Hornblende andesites of practically the same composition are very widespread in Kandavu. They have been described by Wichmann (1882, p. 32) from the island of Ono, by Eakle (1899, p. 586) from Mount Washington, a very recent cone, and by Renard (1888, p. 149) from Vunisea. The specimens collected by the writer, were found at Vunisea, Joma and Namata. A typical specimen from Namara will be described.

The fresh andesite is bluish gray in color, hypocrystalline, and porphyritic. There are abundant phenocrysts of feldspar, 10 to 12 mm. long and 4 to 6 mm. wide; large hornblende needles, 5 to 6 mm. long, are also plentiful. Euhedral phenocrysts of diallagic augite are also present.

The hornblende has an opaque reaction rim about it, such as Renard (1888, p. 151) described as consisting of magnetite and secondary diopside. Though the hornblende has changed to diopside within its mass, the larger part of the reaction rim appears to consist of magnetite. The hornblende is a basaltic, pleochroic variety; yellow // X, darker yellow // Y, and olive yellow to brown // Z.

Analysis gave the following result:

SiO_2	59.70
TiO_2	0.45
Al_2O_3	16.59
Fe_2O_3	1.70
FeO	3.56
MnO	0.05
MgO	4.18
CaO	6.18
Na_2O	3.97
K_2O	2.37
H_2O	1.10
P_2O_5	0.22
	100.07

Norm	
Quartz	7.80
Orthoclase	14.46
Albite	34.06
Anorthite	20.02
Diopside	8.06
Hypersthene	11.10
Ilmenite	.91
Magnetite	2.55
Apatite	.31
	99.27
Water	1.10
	100.37

The position in the Norm classification is:—

Class II	Dosalane,
Order 5	Germanare,
Rang 3	Andase,
Subrang 4	Andose.

A hornblende andesite from Sepulchre Mountain, Yellowstone National Park, closely resembles the Kandavu variety. (Washington, 1903, p. 275).

3) *Hornblende-biotite Andesite.* The specimen was collected from a series of flows, forming low, late-mature hills near the sea-coast, at Vathilea.

The fresh rock is of a bluish slate color, somewhat vesicular, and porphyritic. Phenocrysts of feldspar and hornblende, 5 to 6 mm. long and 1 to 2 mm. wide, with an occasional olive-tinted biotite, are set in a purplish, light gray matrix.

The phenocrysts of feldspar are most abundant and form 30 to 40 per cent of the rock. They are not zoned and have the composition of a basic andesine, or acid labradorite, ($Ab_{52}An_{48}$).

The hornblende phenocrysts are pleochroic; colorless // X, yellow // Y, and olive yellow // Z. The reaction rims of magnetite, described in the other hornblende andesites, are lacking here. Augite also is absent.

The ground-mass has a pilotaxitic texture and consists almost entirely of feldspar.

4) *Olivine Andesite.* The central segment of Kandavu, east of the hornblende andesite area, which extends to the valley east of Namata, is composed of olivine andesite. Specimens of this type of rock were collected at Matasu and Kama. The specimen from Matasu will be described. It was taken from a residual boulder on a low, lateritized hill, 50 to 60 feet high, near the sea-coast.

The fresh andesite is a dark, slate-colored rock, hypocrystalline, porphyritic, and massive. Rounded phenocrysts of feldspar, 3 to 4 mm. in diameter, and phenocrysts of olivine and augite are scattered through a glassy matrix.

The larger feldspars are more acid and have the composition of an acid andesine, $Ab_{70}An_{30}$, whereas the smaller feldspars, probably a second generation, represent acid labradorite, $Ab_{55}An_{45}$. There are zonal inclusions of glass in the larger phenocrysts.

The augite phenocrysts are repeatedly twinned on the front pinacoid and are distinctly euhedral. Olivine is present, in scattering crystals which have largely altered to serpentine.

The texture of the ground-mass is hyalopilitic.

5) *Olivine Basalt.* A central, N.-S. ridge extends through the island of Ndavuni, which lies north of the island of Ono. At the western foot of this ridge, near the center of the island, the specimen of basalt was collected.

It is fresh, greenish black, holocrystalline and very heavy. Phenocrysts of black aügite, 5 to 7 mm. long and 4 to 6 mm. wide, are abundant. Phenocrysts of olivine are less plentiful.

In thin section, small phenocrysts of feldspar are seen to be most abundant. They have the composition of labradorite, $Ab_{45}An_{55}$.

The structure of the ground-mass is pilotaxitic; minute feldspar needles form a mat in which rounded crystals of augite and magnetite occur. The proportion of feldspar to augite is approximately 2 to 1.

Solo Rock.

Andesitic tuff. A single point of rock less than a hundred yards in diameter rises within a circular reef, just north of the Great Astrolabe reef which surrounds Kandavu. On this rock the Solo light-house is situated. The rock is but 8 or 10 feet above the sea. Several specimens, all tuffaceous and andesitic, were collected. Augite, basic andesine, and rare biotite appear in the lava of the fragments.

PETROLOGY OF THE FIJI ISLANDS.

As stated previously, the igneous rocks, collected during the expedition, are not sufficiently numerous or characteristic to serve as a basis for a full petrologic discussion. By comparing personal observations with those of other writers, an attempt will be made, however, to state a few generalizations.

Association of Plutonic Rocks.

Gabbros and diorites have been described from Vanua Levu, and gabbros, diorites, granites, and foyaites, from Viti Levu. Sufficient field-work has not yet been done to show the exact nature of the association, though it is known to be close. The granites and diorites of central Viti Levu, collected by the writer, grade into one another. The texture of the gabbro from the same district allies this rock with the more acid types and it was thought probable that they were all of the same generation.

As the contacts of the plutonic rocks with the sediments which they intruded were not found, no more explicit statement can be made concerning the relations of these rocks.

Volcanic Succession in Viti Levu.

The earliest known lavas in Viti Levu are andesites and rhyolites. No period of erosion is known to separate the flows of these two rock types and they were both extruded in a period preceding the deposition of the folded sediments of the central part of the island. Which of the two types was extruded first has yet to be determined.

After the uplift and folding of the sediments of central Viti Levu, a second period of volcanic activity occurred. This has been referred to as the second andesitic period but in reality basaltic extrusions also occurred in this period. The criteria for rocks of this period are:—1) they have low dips; 2) they overlie the folded sediments of the interior; and 3) pebbles from them occur in the basal conglomerate of the coastal-plains series.

There must have been a considerable period of time between the uplift and folding of the sediments of the interior and the deposition of the coastal-plains series. It is not strange, therefore, to find boulders of olivine basalt in the basal conglomerate underlying the marls near Suva and andesitic pebbles in the analogous basal conglomerate in the Singatoka district.

A study of the distribution of the volcanic rocks in Viti Levu, as given by Cochrane (1911), shows that the coastal hills of the western part of the island, which are assigned to the second andesitic period, are composed of augite andesites and hypersthene-augite andesites. The head waters of the Waimanu and Waindina rivers, northwest of Suva, drain a country underlain by hornblende andesites, though near the coast in the vicinity of Suva, basalts are found.

It is probable that in the period designated as the second andesitic period, a considerable variety of lavas were extruded. The problem of their relative ages has yet to be solved, though from the amount of dissection suffered by the augite andesites and hornblende andesites of western Viti Levu and the Waimanu district, as compared with that affecting the basalts near Suva, the basalts appear to be the more recent.

The volcanic rocks which intrude the uplifted coastal series of southwestern Viti Levu are basalts or basaltic andesites.

The tentative succession of lavas for Viti Levu is, therefore, as follows:—

First epoch — andesite, rhyolite,

Second epoch — hypersthene-augite andesite, hornblende andesite, augite andesite, basalt,

Third epoch — basalt.

Erosion intervals separate the groups. Between the first and second periods of volcanics occurred the folding movements which disturbed the interior sediments.

Comparison of the lavas of Ovalau, Mbengha, and the Yasawa Group with those of Viti Levu.

A hornblende andesite from Ovalau has been described by Wichmann (1882, p. 34). The rocks of Mbengha are basalts, but, while one variety is characterized by olivine and augite, another approaches a hornblende andesite and contains hornblende and augite. The rocks described from the Yasawa group are basalts and hornblende andesites. The prevailing flows of the islands are basalts.

It has been stated previously, (Part I, page 19), that the basalts of the Yasawa group were extruded after the uplift of the limestone islands which belong to the same general period as the coastal sediments of Viti Levu. Because of the relation of the basalts to the Yasawa limestones, the main islands of the group are thought to have been built during the last or basaltic period. The andesites of these islands may, therefore, be remnants of flows dating from the earlier andesitic period. The same may be said for the hornblendic rocks of Mbengha and Ovalau.

Volcanic Succession in Vanua Levu.

The lavas erupted upon the eroded gabbro, near Mount Avuka, are similar to the andesites of Viti Levu which were assigned to the first andesitic period. Pitchstones were found associated with these rocks and it was inferred that certain of the rhyolitic deposits were of the same period; but, in general, the erosion of the rhyolites of northeastern Vanua Levu has not progressed any further than that of the hypersthene andesites. It was, therefore, concluded that some of the rhyolites were extruded in the second andesitic period.

The extrusion of the hypersthene andesites took place, in large part, beneath the sea. Their ash and agglomerates form palagonitic tuffs which were not uplifted until about the same date as the uplift of the marls of the coastal series in Viti Levu.

The second andesitic period of Vanua Levu is considered to have closed with the uplift just mentioned.

From Guppy's description, the olivine basalts forming the promontory at the extreme southwestern end of Vanua Levu, were not erupted beneath the sea; and their sculpturing is so recent that it is believed they were extruded after the uplift of the hypersthene andesites.

In general outline, the succession of lavas in Vanua Levu is not unlike that in Viti Levu. The succession is as follows: —

First epoch — andesite, rhyolite,
Second epoch — rhyolite, hypersthene andesite,
Third epoch — basalt.

It should be stated that the folded sediments of Viti Levu are not found in Vanua Levu and that the deposits of the second andesitic period have no known period of erosion separating them from the first andesitic period. Therefore, it would, perhaps, be preferable to consider the first and second periods, indicated above, as one. For the sake of comparison with Viti Levu, the two periods are retained. In other words, after the erosion of the gabbro of Vanua Levu, the island subsided and was not again uplifted till the period of uplift of the coastal sediments of Viti Levu. During this time of depression, no marls or sandstones are known to have been deposited above the gabbro; instead there are a series of palagonitic tuffs.

Volcanic Succession in the Lau Group.

Three periods of vulcanism have been recognized in the Lau islands. Little is known of the first period which is now represented by pyritized, pumice-tuffs. The lavas of the second or andesitic period are prevailingly andesites, though they are allied to augite basalts and, occasionally, as in the island of Lakemba, carry a little olivine. The analysis of the andesitic basalt from Thikombia-i-lau (p. 126) is typical of this series.

The andesitic period is considered to be contemporaneous with the second andesitic period of Viti Levu and Vanua Levu. In Lakemba, the augite andesites appear to merge into basalts. The occurrence of both basalt and augite andesites in the larger islands has already been noted. It is possible that these types were erupted at approximately the same time and represent phases of a common magma.

The third, or basaltic period, is characterized only by olivine basalts in the Lau Group. The analysis of a basalt from Yanu Yanu (p. 124) is typical of the lavas of the third period.

The volcanic succession is therefore, as follows: —

First epoch — rhyolites?
Second epoch — andesites or basalts.
Third epoch — basalts.

Volcanic Succession in the Kandavu Group.

No unconformities are known between the volcanic rocks of Kandavu and, hence, no exact dates can be assigned to the various rock types. Judging from the erosion of the islands, three periods may be recognized. Near Vunisea, hornblende andesites are eroded to late maturity; farther northeast, augite andesites and olivine andesites are eroded to early maturity. The very recent peak of Mount Washington, is said to consist of hornblende andesites (Eakle, 1899, p. 586). Again, hornblende andesites are described from Ono, which has a submature topography, whereas the northern island of Ndravuni, with a very similar topography, is composed of olivine basalts.

Thus, while hornblende andesites have prevailed in all periods of eruptivity, it is thought that the order, hornblende andesite, augite andesite or basalt, hornblende andesite, approaches nearest the truth.

General Summary of the Volcanic Successions in Fiji.

Reviewing the succession of lavas which have been recorded from the various islands, the first andesitic period is recognized only in the two large islands of Viti Levu and Vanua Levu. Rhyolitic rocks are associated with this period. The second andesitic period is recognized in all the islands in which volcanic rocks are exposed. A diversity of lavas were extruded in this period. From Viti Levu, olivine basalts, hornblende and augite andesites are reported; from Ovalau, hornblende andesites; from Vanua Levu, augite andesite, augite-hypersthene andesite, hornblende andesites, and rhyolites; from the Lau Islands, augite andesites and basalts; and from Kandavu, basalts, augite and hornblende andesites.

The products of the later, basaltic period are not so widespread as those of the previous periods. Basalts are known from Viti Levu; olivine, augite and hornblende basalts from Mbengha; basalts from the Yasawa islands; basalts from Vanua Levu; and basalts from the Lau group.

In view of the diversity of lavas assigned to the second andesitic period, it is important to note that the two most recent eruptions known in Fiji have a very diverse composition. The recent cones of Taviuni gave vent to basaltic flows, whereas Mount Washington, Kandavu, is a hornblende-andesite volcano.

Differentiation in the Lavas of Fiji.

The discussion of the volcanic succession has brought out an important relationship between the rocks of Fiji. In the islands of the Lau Group, which appear to be of recent origin, there is little diversity in the lavas of the two known periods. Basalts, or augite andesites related to basalts, characterize both periods.

On the other hand, within the larger islands, the diversity of lava is great. It is pertinent to inquire, why hornblende is so frequently found in the rocks of Kandavu, Mbengha, Viti Levu and Vanua Levu and is not known on the rocks of the Lau islands.

In most cases, the hornblende gives evidence of being resorbed into the magma and of breaking down into augite and magnetite. It apparently was not in equilibrium with the magma at the time of its solidification. If it is true that hornblende and biotite form only in the presence of magmatic gases, especially water, the loss of these gases on extrusion may be considered to be the cause of the instability of the hornblende in the magma. Thus, in the case of an open vent in which gases were freely given off, hornblende would not form, whereas if the gases were retained for any reason during a period of dormancy, hornblende might develop.

The close association of hypersthene and hornblende in the rocks of Vanua Levu would indicate that the conditions for the formation of the two minerals are quite similar. It is significant that all the hypersthene basalts of Vanua Levu are the results of submarine extrusions. Frank Perret (1917, p. 456) has recently described a flow from Stromboli which entered the sea. He emphasized the rapid formation of a flexible, impervious skin and the slight disturbance produced. It would seem probable that the retention of the volcanic gases under such circumstances would allow hypersthene and hornblende to develop.

Hypersthene and hornblende should, therefore, characterize intermittent and submarine volcanoes, whereas the monoclinic pyroxenes should be found near volcanoes having open vents. The hornblende, hypersthene, and augite andesites are closely related to basalts and are considered to be pure differentiates of a primary basaltic magma. Because of insufficient time it was impossible to make a thorough study of the distribution of lavas about individual volcanic vents. Guppy (1903, pp. 62–65) observed that augite andesites were intimately mingled with olivine basalts in the sub-Recent crater of Mount Seatura, western Viti Levu. The writer observed that the ground-mass of olivine basalts in which zoned feldspars occurred usually contained a feldspar more acid than the phenocrysts and that the ferromagnesian mineral present in such a ground-mass was usually augite. The recent experiments of Bowen (1915, p. 47) practically establish the fact that an augite andesite may differentiate by gravity from an olivine basalt.

In conclusion it may be said that the trend of the volcanic succession in Fiji has been from acid to basic types; yet, while this is true, hornblende andesites have persisted in Kandavu from the first. Another striking fact is the persistency of volcanic vents. Few instances are known in which the later, basaltic eruptions have built up independent craters. On the other hand, a number of examples have been given which show that later basaltic cones were formed on or near earlier andesitic volcanoes.

TABLE OF ANALYSES.

	Tonalite from Central Viti Levu (Yellowstonose)	Olivine Basalt from Lautoka, Viti Levu (Andose)	Basalt from Yasawa Is. (Hessase)	Gabbro from Lambasa, Vanua Levu (Hessose)	Andesitic Basalt from Tota, Vanua Mbalavu (Andose)	Olivine Basalt from Yanu Yanu, Exploring Group (Auvergnose)	Basalt from Thikombia-i-lau (Tonalose)	Olivine Andesite from Ono-i-lau (Andose)	Olivine Basalt from Kambara (Auvergnose)	Hornblende Andesite from Kandavu (Andose)
SiO_2	70.00	47.36	50.06	50.01	55.75	48.56	58.30	52.08	45.63	59.70
TiO_2	00.30	0.85	——	1.01	——	2.40	0.80	1.40	——	0.45
Al_2O_3	14.72	19.38	19.38	19.33	16.53	16.30	17.10	17.86	15.56	16.59
Fe_2O_3	1.36	3.60	1.83	1.85	0.53	2.04	2.10	2.22	3.12	1.70
FeO	2.28	6.13	5.54	6.26	7.14	8.61	5.58	5.76	10.81	3.56
MgO	1.37	5.31	6.53	3.51	3.19	8.76	2.70	3.89	8.64	4.18
MnO	0.04	0.11	0.47	0.21	0.55	0.10	0.08	0.10	0.24	0.05
CaO	3.58	10.54	12.06	12.38	9.12	8.22	7.40	8.20	11.52	6.18
Na_2O	3.70	2.69	1.16	2.13	4.24	2.04	3.72	3.67	1.26	3.97
K_2O	1.68	1.74	0.93	0.18	0.95	0.70	0.83	2.07	1.11	2.37
H_2O-	0.50	2.20	1.14	1.55	1.04	1.60	1.15	2.35	0.65	1.10
H_2O+	——	——	0.37	1.85	0.51	——	——	——	0.80	——
P_2O_5	0.06	0.19	——	trace	——	0.30	0.22	0.36	——	0.22
CO_2	——	——	0.31	——	0.32	——	——	——	0.40	——
Total	99.59	100.10	99.78	100.27	99.87	99.63	99.98	99.96	99.74	100.07

Bibliography.

Agassiz, Alexander.

1898. The Tertiary Elevated Reefs of Fiji. Am. Jour. Sci., 4th series, Vol. 6, pp. 165–167.

1899. Coral Reefs of Fiji. Bull. Mus. Comp. Zoöl., Harvard College, Vol. 33.

Andrews, E. C.

1900. Limestones of the Fiji Islands. Bull. Mus. Comp. Zoöl., Harvard College, Vol. 38.

Andrews, E. C. and **Sawyer, B.**

1901. Notes on the Caves of Fiji. Proc. Linnean Soc., N. S. W., Vol. 26, pp. 91–106.

Bowen, N. L.

1915. The Later Stages of the Evolution of the Igneous Rocks. Jour. of Geology, Vol. 23a, Dec. supplement, pp. 11–17.

Brady, H. B.

1888. Notes on the so-called "Soapstones" of Fiji. Quart. Jour. Geol. Soc., London, Vol. 44, p. 1.

Cochrane, N. D.

1911. Rocks of Fiji. Legislative Council Paper, No. 15, Suva, Fiji.

Dall, W. H.

1898. Letter to A. Agassiz. Am. Jour. Sci., Vol. 6, 4th series, p. 165.

Daly, R. A.

1914. Igneous Rocks and Their Origin, New York.

1915. The Glacial-control Theory of Coral Reefs. Proc. Am. Acad. Arts and Sciences, Vol. 51, pp. 157–251.

Dana, J. D.

1844. Report of the American Exploring Expedition, (Wilkes), Geology, pp. 337–352.

1853. Coral Reefs and Islands, New York.

Darwin, Charles.

1842. The Structure and Distribution of Coral Reefs, London.

Davis, W. M.

1914. The Home Study of Coral Reefs. Bull. Am. Geog. Soc., Vol. 46, pp. 561–739.

1915. A Shaler Memorial Study of Coral Reefs. Am. Jour. of Sci., Vol. 40, pp. 223–271.

Eakle, A. S.
1899. Petrographical Notes on some Rocks from Fiji. Proc. Am. Acad. Arts and Sciences, Vol. 34, pp. 581–595.
Gardiner, J. S.
1898. Coral Reefs of Funafuti, Rotuma and Fiji. Proc. Camb. Phil. Soc., Vol. 9, pt. 8, pp. 417–503.
Gerland, G.
1895. Beiträge zur Geophysik, Vol. 2, p. 56.
Graeffe, Edward.
1869. Reisen im Innern von Viti-Levu. Petermann's Geog. Mitt., Gotha, Vol. 15, p. 60.
Guppy, H. B.
1903. Observations of a Naturalist in the Pacific. Vol. 1. London.
Jenson, H. I.
1907. Note on an Occurrence of Copper in Andesite near Lautoka, Fiji. Jour. Royal Soc., N. S. W., Vol. 41, p. 49.
Kleinschmidt, Th.
1879. Reisen auf den Viti-Inseln. Jour. des Mus. Godefroy, Hamburg, Vol. 5, pt. 14.
Marshall, P.
1912. Oceania, Carl Winter, Heidelberg.
Mawson, Sir Douglas.
1905. The Geology of the New Hebrides. Proc. Linnean Soc., N. S. W., Vol. 30, pp. 400 et seq.
Murray, Sir John.
1880. On the Structure and Origin of Coral Reefs and Islands. Proc. Royal Soc. Edinburgh, Vol. 10, pp. 505–518.
Perret, Frank.
1916. The Lava Eruption of Stromboli, Summer-Autumn, 1916. Am. Jour. Sci., Vol. 42, p. 456.
Renard, A.
1888. Rocks from Kandavu, Fiji. Rep. of Challenger Expedition, Physics and Chemistry, Vol. 2, pt. 7, p. 149.
Sherlock, R. L.
1903. The Foraminifera and other Organisms in the Raised Reefs of Fiji. Bull. Mus. Comp. Zool., Harvard College, Vol. 38, pp. 349–365.
Skeats, E. W.
1903. The Chemical Composition of Limestones from Upraised Coral Islands. Bull. Mus. Comp. Zoöl., Harvard College, Vol. 42, pp. 53–126.

Tenison-Woods, Rev. J. E.
1879. On some Fossils from Fiji. Proc. Linnean Soc., N. S. W., Vol. 4, p. 358.

Tyerman, Rev. Daniel, and Bennet, George.
1832. Journal of Voyages and Travels, Boston, Vol. 1, p. 215.

Vaughan, T. W.
1914. Sketch of the Geological History of the Florida Reefs, etc. Jour. Wash. Acad. Sci., Vol. 6, pp. 26–34.
1916. Some Littoral and Sublittoral Physiographic Features of the Virgin and Northern Leeward Islands, etc. Jour. Wash. Acad. Sci., Vol. 6, pp. 53–66.

Washington, H. S.
1903. Chemical Analyses of Igneous Rocks. U. S. G. S. Prof. Paper No. 14.

Wichmann, Arthur.
1882. Petrography des Viti-Archipels. Tschermaks Mitth., Vol. 5, (New Series), pp. 1–60.

Wharton, Rear Admiral W. J. H.
1897. Foundations of Coral Atolls. Nature, Vol. 55, pp. 390–393.

Woolnough, W. G.
1903. The Continental Origin of Fiji. Proc. Linnean Soc., N. S. W., Vol. 28, pt. 3, pp. 457–540.
1907. A Contribution to the Geology of Fiji. Proc. Linnean Soc., N. S. W., Vol. 32, pp. 431–474.

Wright, C. H.
1916. Soils of Fiji. Bulletin 9, Agricultural Dep't. Suva, Fiji.